STRIP-MINE REHABILITATION IN NAMAQUALAND

BY

ANÈL SCHMIDT

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SUPERVISOR:

PROF. S.J. MILTON

CO-SUPERVISOR:

A. LE ROUX

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I, ANÈL SCHMIDT, HEREBY DECLARE THAT THE WORK CONTAINED IN THIS THESIS IS MY OWN ORIGINAL WORK AND THAT I HAVE NOT PREVIOUSLY IN ITS ENTIRETY OR IN PART SUBMITTED IT AT ANY UNIVERSITY FOR A DEGREE.

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SUMMMARY

Namaqualand has a very unusual diversity of plant life, with many endemic plant species. The fundamental question of this thesis is how this system, damaged by strip-mining activities, can be rehabilitated. The aim was to base the rehabilitation methods on ecological processes.

In order to answer this question an overview of the relevant literature was needed in order to identify possible research needs and also to evaluate the work that has been done in the field of strip-mine rehabilitation in arid areas. An understanding of community and ecosystem dynamics would help to establish aims and methods for site-specific rehabilitation. In Namaqualand, South Africa, there is also a need for experimentation to establish which of the many factors is most limiting to long-term ecosystem recovery.

It is important to have a good knowledge of the successional processes and disturbance history of the land which needs to be rehabilitated. The vegetation on unmined areas and mined areas of different ages and treatments after mining, were sampled. It was shown that some areas could be expected to show a large degree of recovery in the space of a few years, whilst others would show little or no recovery over a period of decades. It is important to recognise rehabilitation as a gradual process that takes place at different rates in different areas and in different years. The planting of *Atriplex nummularia* and sowing of *Atriplex semibaccata* did not facilitate the return of indigenous, perennial species, but rather seem to inhibit their return.

In view of the importance of topsoil in terms of the fertility of the soil and the seed bank present in the topsoil, the influence of topsoil removal and stockpiling due to strip-mining activities were tested. The soil fertility was tested by means of radish bioassays and soil laboratory analysis, whilst species diversity and richness were tested with seedling emergence trials. As expected a higher plant species diversity was found on the unmined soils and radishes grew larger on these soils. The topsoil deteriorated in terms of plant species richness, diversity and soil fertility whilst it was stockpiled. Direct replacement of topsoil would ensure a planting medium closer to the pre-disturbance level that could lead to fairly rapid and successful recolonization of the mined area.

Successful plant recruitment also depends on the microsites to which seeds are dispersed. The effect that different microsites had on seed germination, seedling growth and survival was tested. It was found that micro catchments always yielded the highest numbers. The establishment and survival of seedlings in the other microsite types (under single shrubs, under clumped shrubs and in the open) varied, depending on the amount of rainfall received in the particular year. Lastly, I experimented with the translocation of three local, indigenous, succulent plant species. These plants were transplanted either in clumps of three together or alone, since I hypothesized that planting them together would facilitate their survival. However, it was found that it depended largely on the morphology of the plant and the amount of rainfall

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received in a particular year, whether these plants will compete with each other for limiting resources or facilitate each other's survival.

The thesis contributes to the understanding of vegetation dynamics in the Succulent Karoo after strip-mining has taken place. Guidelines are provided based on ecological processes, for strip-mine rehabilitation in the Succulent Karoo.

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OPSOMMING

Namakwaland is bekend vir sy ongewone diversiteit van plante, met baie endemiese spesies. Die fundamentele vraag wat deur hierdie tesis gevra word is hoe hierdie sisteem, wat beskadig is deur oppervlak mynbou, gerehabiliteer kan word. Die doel is om die rehabilitasie metodes te baseer op ekologiese prosesse.

'n Oorsig van die relevante literatuur was nodig om moontlike areas van verdere navorsing te identifiseer en ook die navorsing wat reeds gedoen is oor rehabilitasie van oppervlak myne in ariede gebiede, te evalueer. 'n Goeie begrip van gemeenskap en ekosisteem dinamika sal help om doelwitte en metodes daar te stel vir die rehabilitasie van spesifieke areas. Dit is ook nodig om in Namakwaland, Suid -Afrika, uit te vind watter van die baie faktore, die lang-termyn herstel van 'n ekosisteem, die meeste verhinder.

Dit is baie belangrik om 'n goeie kennis te hê van die versteurings geskiedenis van die area wat gerehabiliteer moet word, asook die suksessionele prosesse wat werksaam is. Plantegroei van areas wat op verskillende tye gemyn en verskillend behandel is, asook ongemynde areas is ondersoek. Sekere areas het 'n groot mate van herstel gewys in 'n tydperk van 'n paar jaar, terwyl ander, min of geen herstel oor 'n periode van dekades getoon het nie. Dit is belangrik om rehabilitasie as 'n geleidelike proses te sien, wat teen verskillende tempos plaasvind tydens verskillende jare en in verskillende areas. Daar is bevind dat die plant van *Atriplex nummularia* asook die saai van *Atriplex semibaccata* nie die terugkeer van inheemse, meerjarige spesies bevoordeel nie, maar dit eerder inhibeer.

Aangesien die bo-grond so belangrik is in terme van die grondvrugbaarheid en ook die saadbank wat teenwoordig is, word die invloed van die verwydering en opberging van die bo-grond getoets. Die grondvrugbaarheid was bepaal deur groei-toetse op radyse en laboratorium analise op die grond te doen. Die plant spesie diversiteit en rykheid was bepaal met 'n saad ontkieming studie. In ooreenstemming met die verwagte uitkoms, was die plant spesie diversiteit hoër op die ongemynde bo-grond en die radyse het groter geword op dieselfde grond. Dit kom voor asof die plant spesie diversiteit en rykheid, asook die grond vrugbaarheid afneem met tyd wat die bo-grond geberg word. Die direkte verspreiding van die bo-grond nadat dit verwyder is, sal 'n medium vir die plante verseker wat nader is aan die vlak voordat die grond versteur is. Dit sal ook sorg vir redelike vinnige en suksesvolle terugkoms van plante op die gemynde grond.

Die suksesvolle vestiging van plante hang ook af van die mikro areas (klein areas in terme van die grootte van 'n saad, wat 'n eie mikro-klimaat vorm), waarna saad versprei word. Die effek van sulke mikro-gebiede op die ontkieming van saad, die groei van die saailinge en die oorlewing van die saailinge was bepaal. Mikro-water- opvanggebiede het in al drie

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bogenoemde gevalle die hoogste syfers getoon. Die vestiging en oorlewing van saailinge in die ander mikro-gebiede (die area onder enkel struike, die area onder groepe struike en oop areas) het gevarieer afhangend van die hoeveelheid reënval wat ontvang is in die spesifieke jaar. Laastens, is daar ge-eksperimenteer met die oorplant van drie plaaslike, inheemse, sukkulente spesies. Hierdie plante was alleen geplant of in groepies van drie, bymekaar. Die hipotese was dat hul oorlewingskanse beter sal wees as hulle saam geplant word. Dit was egter bevind dat die hoeveelheid reënval in 'n spesifieke jaar en die morfologie van die plant, bepaal of hulle sal kompeteer vir die beperkte bronne en of hulle deur saam te groei hul oorlewingskanse sal verhoog.

Hierdie tesis dra by tot die verstaan van die plantegroei dinamika in die Sukkulente Karoo nadat oppervlak mynbou plaasgevind het. Riglyne vir die rehabilitasie van oppervlak myne, gebasseer op ekologiese prosesse, word ook voorgestel.

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CONTENTS

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Stellenbosch University http://scholar.sun.ac.za

Stellenbosch University http://scholar.sun.ac.za

LIST OF FIGURES

Stellenbosch University http://scholar.sun.ac.za

Stellenbosch University http://scholar.sun.ac.za

LIST OF TABLES

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CHAPTER 1

GENERAL INTRODUCTION AND THESIS STRUCTURE

"We have cycled from native to disturbed systems and back. It is not clear how close we are to that desirable climax - truth - but I fear that we are still in our pioneer stage and that we will need to cycle between native and reclamation ecosystems for years to come, with both systems helping us to develop an integrated systems approach that would not be possible working with either alone" (Author unknown).

Surface mining is unavoidably an environmentally destructive process. The properties of mined soils make them a poor medium for plant growth and natural recolonisation on these soils is slow, particularly in arid regions (Sharma & Gough, 1999; Abu-Irmaileh, 1994). The Succulent Karoo, a winter rainfall desert in the western part of South Africa (Desmet & Cowling, 1999) is rich in minerals, deposited by evaporation and igneous activity. A number of sites in this region are presently being surface mined for gypsum, lime, marble, titanium, and zircon. Mining activities in this arid region are likely to increase as a result of the richness of the deposits and because mining is a major job provider in this economically undeveloped region. There is no doubt that mining is a necessary and essential component of Namaqualand's economy. The industry accounts for more than half of the gross geographic product of the region and is its largest employer. The industry, however has, until very recently, not recognised the fact that it operates in an area of great biodiversity and that its impacts carry a cost. The tourism potential of large areas of coastline could never be fully restored. New legislation does require an assessment of the impacts that further mining operations would have on the environment as well as rehabilitation procedures (Cowling & Pierce, 1999). Surface mining activity poses a threat to the conservation of the unusual and species rich flora of this part of the Succulent Karoo.

The Succulent Karoo occurs to the south and west of the Nama Karoo and is characterised by a high diversity of leaf-succulent genera and species. The winter rainfall of the area is low, but relatively predictable and the absolute and average minimum temperatures are high compared to other parts of the Karoo (Desmet & Cowling, 1999). Dwarf, succulent shrubs of the families Mesembryanthemaceae, Crassulaceae and Euphorbiaceae are prominent. Annuals mainly from the family Asteraceae forms an important component, especially on disturbed landscapes in spring (Hoffman & Cowling, 1987). Grasses are not very common, except in some sandy areas and are mostly of the C_3 type (Low & Rebelo, 1998). The Succulent Karoo is known as one of the world's biodiversity hotspots, since it contains a great diversity of succulent plant species, the greatest in the world. The spring flower displays attracts many tourists each year from across the globe. The

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income generated from tourism then boosts the local economy. Considering these facts, there is no doubt that the area needs to be conserved.

The mining operations may generate public awareness and place an economic value on the land, but at the same time many plant and animal species may be endangered (Milton *et al.*, 1997). The impacts of these mining activities on succulent plant populations are still unquantified. The changes in microtopography and salinity caused by strip-mining and the lack of information on establishment requirements of indigenous plants are among the problems that face restoration ecologists. Information on factors limiting recolonisation of denuded and altered soil in the Succulent Karoo is urgently needed to restore lost productivity and maintain species diversity (Milton *et al.*, 1997). Managers of mine sites have to contend with various limitations. The location of the ore body could be in an ecosystem that is inherently difficult to deal with, there could also be technical and financial difficulties in the material available for rehabilitation and the recreating of the original landforms. The high cost of rehabilitation forces careful planning to avoid getting it wrong, which results in delays and expense, whilst there is no agreed set of criteria or methodology to assess completion criteria. Limited as they are by soil moisture, arid regions cannot economically support intensive or costly revegetation practices, since the expenditure on rehabilitation is not justified by economic returns from the land. Seeds of plants, which reproduce easily and quickly under drought, must be selected for restoration purposes (Abu-Irmaileh, 1994). In arid areas it is also always a problem to recommend an acceptable time frame for rehabilitation and the aesthetic values of the final appearance of rehabilitation can be very subjective. Other limitations are the uncertainty of establishing a new biological system and spatial limitations for wastes and increasing haulage costs. Lastly, it is legally binding to rehabilitate without causing offsite damage to properties in close proximity of the mining operations (Lanz, 1997; DEAT, 1999). The cost of minimising environmental impacts has to be weighed against social issues as the inevitable "end of lifetime" of specific mines are approached within the next decade or two (Mackenzie & Molyneux, 1996). This could result in ghost towns being left behind, which were depended on the mining activities. The most efficient level of output of mineral production will be that which maximizes the net benefit to society, assuming that this is positive (Azcue, 1999).

Explicit objectives and criteria do not exist for restoration situations in the Succulent Karoo. There is therefore a need for the development of guidelines for mine rehabilitation in these areas. These guidelines would be of great use to the government and private sector. Different rehabilitation methods need to be tested and evaluated in order to find the most successful and cost-effective methods. There is a need, however to understand ecosystem processes before any successful rehabilitation can be attempted.

There are two major factors to contend with when rehabilitating a strip-mined site, which are soil quality and revegetation. For seeds to germinate and vegetation to establish, the soil should contain the essential nutrients for plant growth. The availability of suitable microsites to capture

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seeds and to protect seedlings against the harsh environmental conditions is also of great necessity. Plant propagules should be present in the soil or should be supplied externally to be able to revegetate the area.

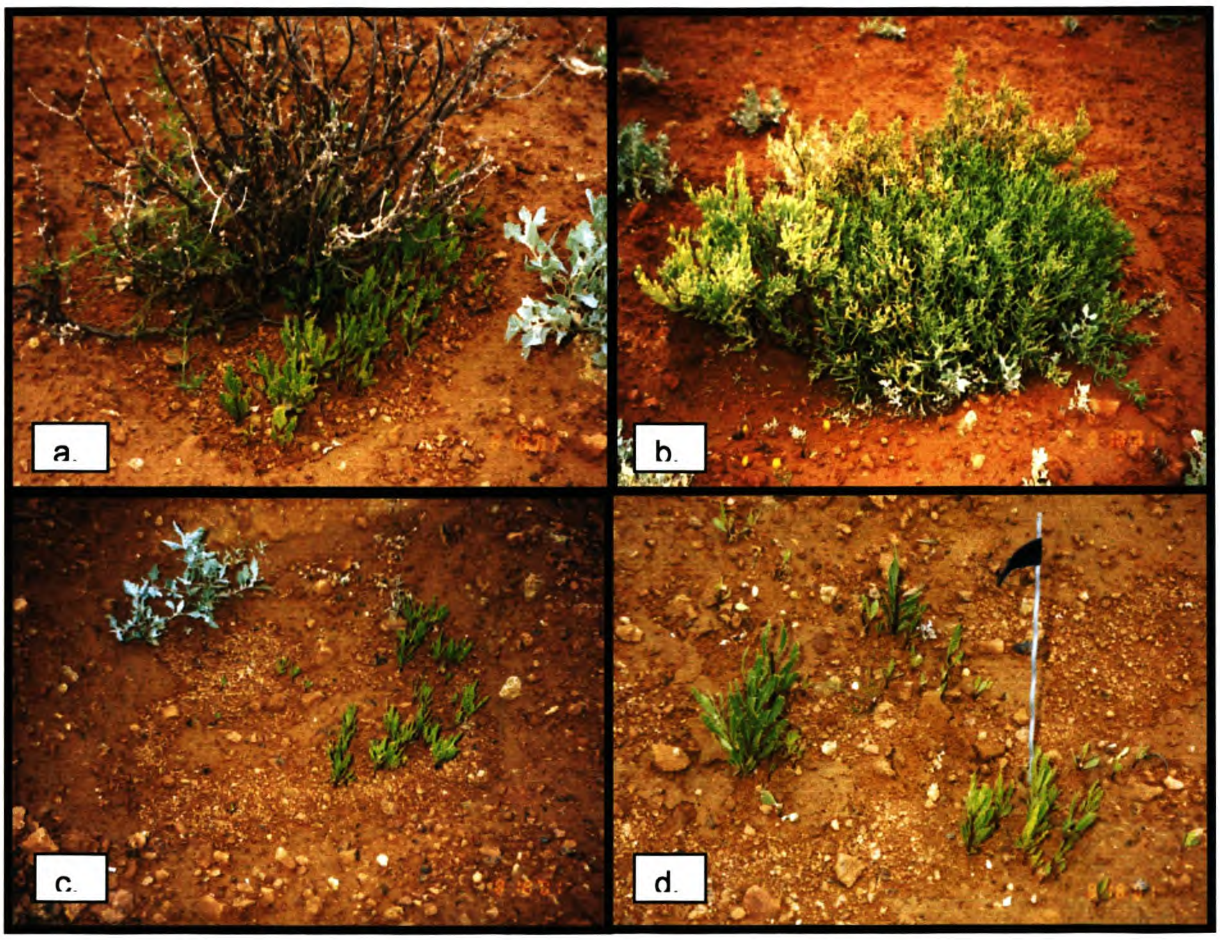

Figure 1.1: a.) Isolated shrub with *Tripteris sinuata* seedlings underneath it. b.) Clump of three succulent species. c.) Micro catchment with *Tripteris sinuata* seedlings. d.) Open area with *Tripteris sinuata* seedlings.

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Figure 1.2: a.) A recently backfilled area. b.) Undisturbed vegetation in August 2001. c.) Alien species colonizing a mined area. d.) Experimental planting of *Atriplex nummularia*.

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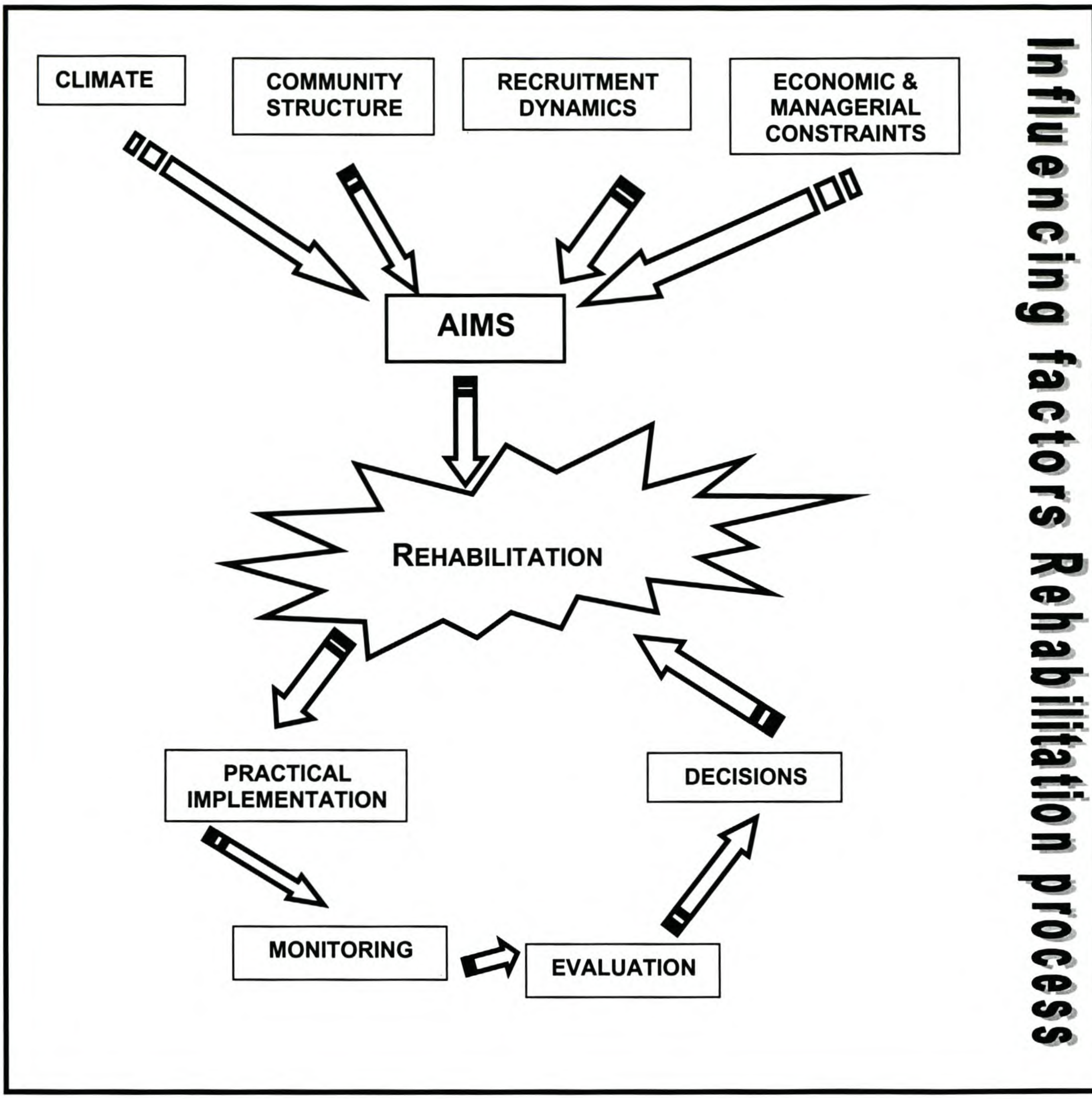

Figure 1.3: A conceptual model illustrating the process of rehabilitation and the factors influencing the aims of rehabilitation.

There are many factors to take into consideration in the rehabilitation process of a strip-mined area. These are summarised in Figure 1.3.

In this thesis I will evaluate methods for rehabilitation of a strip-mined site, taking into consideration the recruitment dynamics and community structure of plant populations and also include some practical issues, economic and managerial constraints in this arid, winter rainfall area (Figure 1.3). I will use these results to draw up some useful guidelines for rehabilitation in arid, winter rainfall areas.

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I will start the thesis with a review of the relevant literature on rehabilitation in arid winter rainfall areas, with particular reference to the Succulent Karoo of South Africa. The review focuses on the aims of rehabilitation, recruitment dynamics, community structure, practical issues in rehabilitation, and economic and managerial constraints in arid, winter rainfall areas. It also identifies areas for further research. The natural succession of mined areas in the Succulent Karoo is very slow. Chapter 3 addresses this issue by means of a vegetation survey in which mined areas of different ages and different treatments are compared (see Figure 1.2 for pictures of some of these areas). With the knowledge of the natural succession rate of the area, I proceed to investigate the influence of the stockpiling of the topsoil on the fertility and the natural seedbank of the soil (Chapter 4). If the soil quality is high and if there are seeds present in the soil, germination of these seeds should take place if they find suitable microsites in which they can establish and grow. Chapter 5 addresses the germination, survival and growth of *Tripteris sinuata* and *Dimorphotheca sinuata* sown in different microsites after strip-mining (see Figure 1.1). The natural vegetation is characterised by a patchy structure in which shrubs grow in close association with each other. The survival, growth and seedset of *Aridaria noctiflora, Drosanthemum deciduum* and *Psilocaulon dinteri* were therefore established after translocation to a mined area, whilst subjected to different experimental arrangements (Chapter 6, Figure 1.1). General conclusions are drawn in Chapter 7.

Study Site

Location and vegetation

The research was undertaken at a gypsum strip-mine, 5km north of Vanrhynsdorp (31^0 33.6" S and 18^0 45.2" E). It is located in the Cape Province of South Africa on the western side of the country. The vegetation of the study area is classified by Acocks (1975) as veld type 31, Succulent Karoo and by Low & Rebelo (1998) as Lowland Succulent Karoo. It is a low shrubland, dominated by members of the Mesembryanthemaceae, especially species of *Ruschia, Drosanthemum, Malephora* and *Delosperma.* Annuals and geophytes may be common after good rains but perennial grasses are scarce. Abandoned crop lands (old lands) and disturbed areas are often dominated by *Galenia africana.* The vegetation is spatially discontinuous with a low total cover. Isolated patches of plants occur within areas of bare soil. Soil mounds are present beneath plant canopies on flat areas.

The mined areas are composed of mainly invasive species e.g. *Salsola kali, Atriplex semibaccata* that are medium height shrub species. The difficulty with spreading the topsoil evenly across the mined area results in the vegetation growing back patchily, with large areas of bare, hard, rocky soil.

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Some experiments were done by the mining company with the sowing of *Atriplex semibaccata* and the planting of *Atriplex nummularia* on some of the mined areas. Other areas were tilled and wheat planted, over a period of three years. This however was unsuccessful and no useful crop could be harvested.

Geomorphology and Soils

The substratum consists of highly deformed and metamorphosed rocks of the Namaqualand Metamorphic Province, which is dominated by granite gneisses. The soils of the area consist of an orthic A horizon, therefore a lack of an organic, humic, vertic or melanic topsoil and described as Red apedal or neocutanic. A cemented sediment layer (proto-silcrete) of laterite known as duripan or dorbank follows, which in turn is followed by a gypsic horizon (Soil Classification Working Group, 1991). Iron oxides give the soil a red colour and non-swelling clays are present. Mining mixes fractured rocky deposits with topsoil so that after mining the soil is rockier, with less topsoil present. The different horizons mentioned above are disturbed during the mining process and therefore the soil on the post-mining surface will be a mix of topsoil, subsoil and dorbank. This will influence water infiltration, the ability of the soil to retain water and other resources, and also influence the pH and salinity of the soil and therefore vegetation establishment on these soils. It is speculated that the dorbank horizon acts as a water barrier, which retains the water within the rooting depth of the vegetation. The breaking of the dorbank could therefore seriously disturb the local hydrology and influence vegetation establishment. The slow soil formation of this arid region results in shallow coarse soils with sharp soil boundaries, causing the soils to be very sensitive to degradation.

Climate

The region is characterised by extreme summer aridity with a mean annual precipitation of 145.5mm (Desmet & Cowling, 1999), ranging from 50 to 200mm in the cool season (May to August) (Figure 1.4). During the study period, the annual precipitation at the study site was 78mm for 2000 and 215mm for 2001. Figure 1.5a and 1.5b shows the monthly precipitation and temperatures for both these years, obtained from Vredendal weather station. The average annual maximum air temperature is 23.4^{0}C and the average annual minimum temperature is 8.7^{0}C (Figure 1.4). The hottest and coldest months are February and July respectively, and average evaporation is 7.875mm/month. This region could therefore be classified as a winter-rainfall desert (receives less than 200mm/year) with hot dry summers.

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The low rainfall of the area and extreme temperatures limits the season in which revegetation can take place and also increases the time it would take to establish vegetation, which can support the pre-mining land-use of the area. The low rainfall of 2000 would stunt the establishment of vegetation on the mined area, whilst a high rainfall year for example 2001 (Figure 1.5) greatly increased the rate of establishment and survival of seedlings.

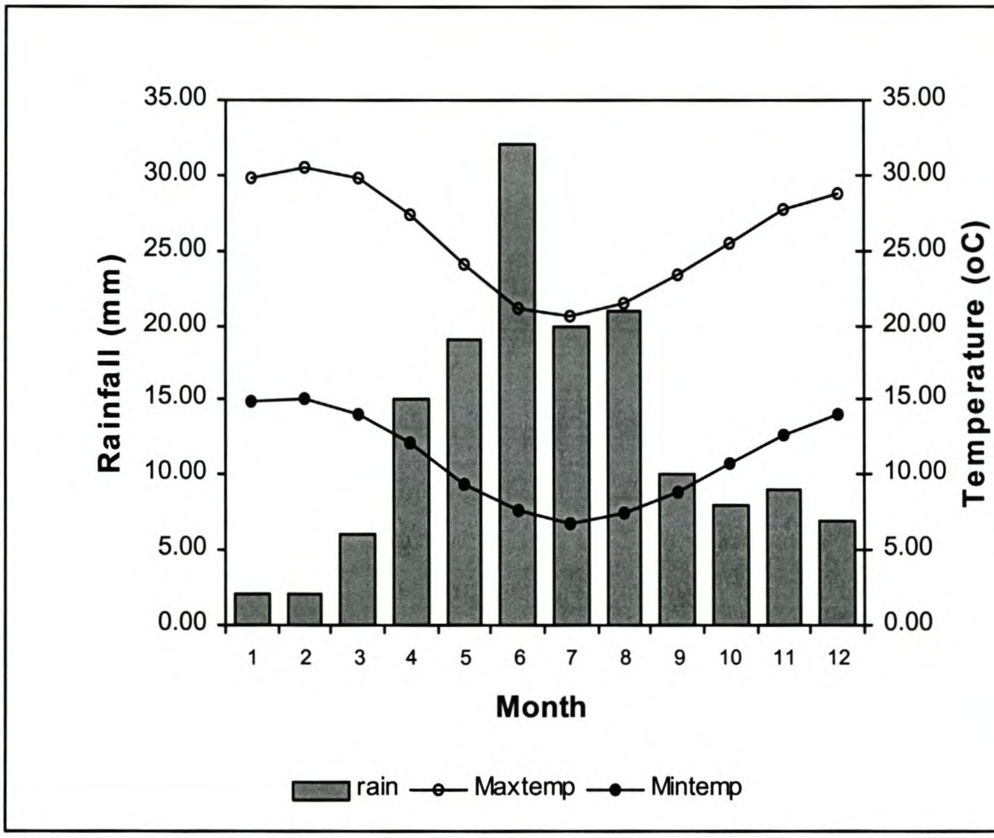

Figure 1.4: The Long-term (29 years, 1961 - 1990) average daily maximum and minimum temperatures and average monthly precipitation for Vredendal weather station (31^0 40' S; 18^0 30' E).

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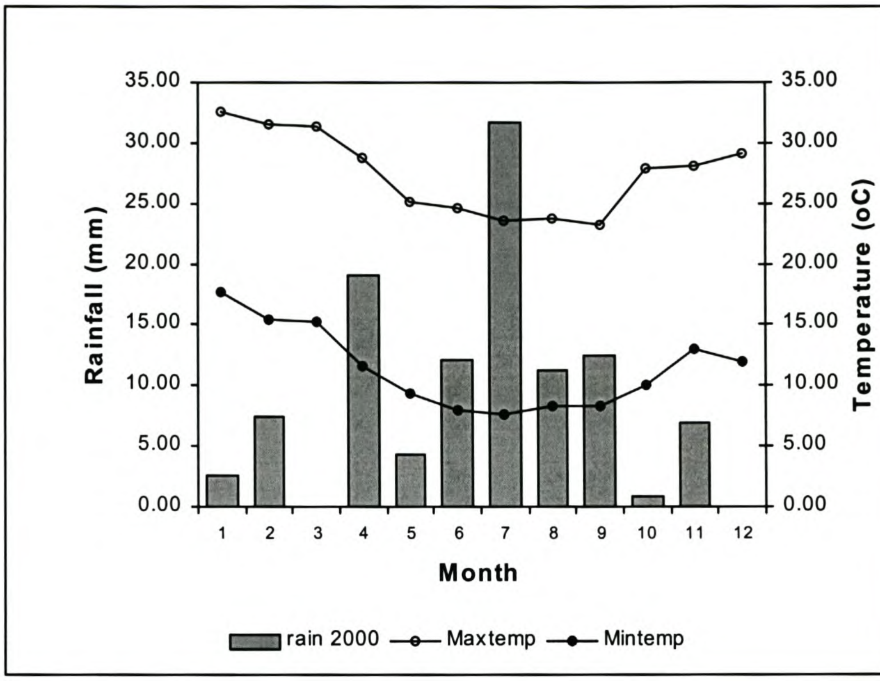

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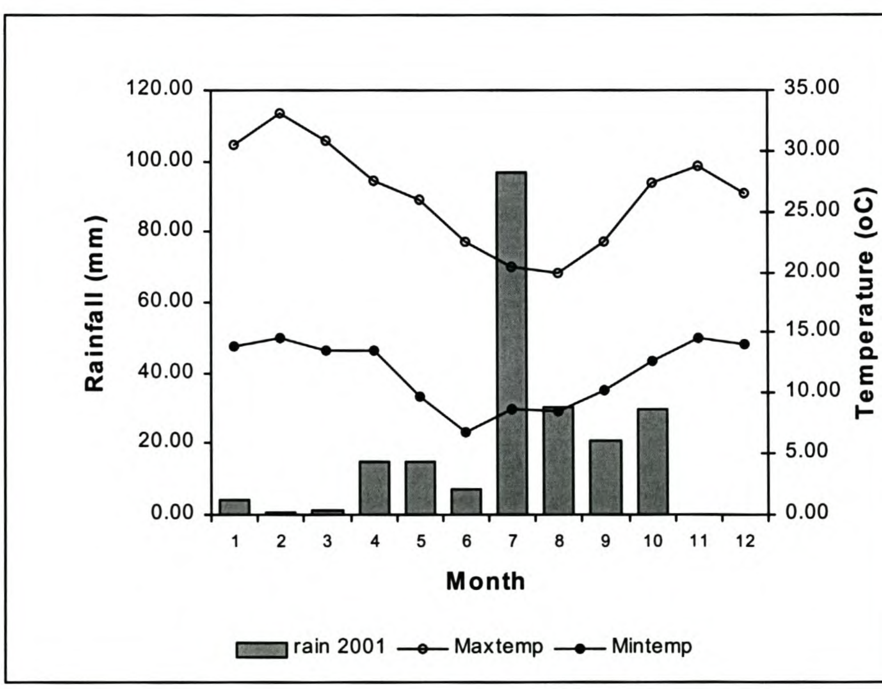

1.5 b

Figure 1.5: a.) The monthly rainfall, average monthly maximum and minimum temperatures for 2000 (Vredendal weather station).

b.) The monthly rainfall, average monthly maximum and minimum temperatures for 2001 (Vredendal weather station).

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The mining method

The mining method involves the removal of vegetation and the first 50mm of topsoil from areas of approximately 1 ha in size. The topsoil, inclusive of the vegetation is then stockpiled towards the sides of the particular quarry. The height of the stockpiles is kept below 3m. The overburden (layer overlying the gypsite) is then removed and placed in stockpiles next to the topsoil (Figure 1.6).

The gypsum, which is mixed with clay, is now removed and is transported to the processing plant. Here the gypsum is separated from the clay in a process where the clay is washed from the gypsum with water. The remaining tailings are then dried and the water is re-used after it has circulated through a series of slimes dams. The dried tailings are replaced in the quarries and the area is backfilled with overburden and then levelled to approximately coincide with the original contours of the landscape as to facilitate drainage of the site. Finally, the topsoil is spread as evenly as possible over the surface (Figure 1.2a). The time it takes for the whole process to be completed varies with the richness of the deposit in each quarry and external factors, such as equipment that fails or labour strikes. The aim is to complete the process within a period of three months. If this process were delayed, it would result in increased topsoil stockpiling time, which could seriously affect the soil quality and viable seedbank (Chapter 4).

Figure 1.6: An open quarry, with tailings being replaced in the foreground and stockpiles of topsoil and overburden in the background.

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CHAPTER 2

STRIP-MINE REHABILITATION IN ARID WINTER RAINFALL AREAS: THE SUCCULENT KAROO OF SOUTH AFRICA

Abstract

Anthropogenic disturbances of ecosystems are a worldwide problem due to ever increasing population rates, especially in developing countries. Humans are forced to make more use of their natural resources, as is the case with strip-mining. A realization by the regulating authorities of many countries, that humans cannot just exploit nature for their own selfish purposes, started legally forcing mining companies to rehabilitate after mineral extraction. An understanding of community and ecosystem dynamics would help to establish aims and methods for site-specific rehabilitation. In Namaqualand, South Africa, there is also a need for experimentation to decide which of the many factors is the most limiting to long-term ecosystem recovery. Rehabilitation should be part of an integrated program of effective environmental management through all the stages of resource development, from exploration to construction, operation and closure. Mine managers in co-operation with regulatory bodies and interested and affected parties need to work together to develop successful strategies to deal with the disturbances of topography, soils and vegetation of surface mined areas in the Succulent Karoo Biome of South Africa. The development of these strategies, within an adaptive approach, would be dependant on regular monitoring to assess the degree of success over time. This review therefore focuses on the aims of rehabilitation, recruitment dynamics, community structure, practical issues in rehabilitation, and economic and managerial constraints in arid, winter rainfall areas.

***Key words**:* arid, strip-mine rehabilitation, Succulent Karoo.

Introduction

Increasing human pressures on the land, both directly through mining, and agricultural transformation and indirectly through habitat fragmentation, inappropriate management practices, and alien invasions are threatening the survival of plant communities and their genetic resources (Wood *et al.,* 1994). In arid shrublands altered stable states can occur if a community is pushed beyond its thresholds of resilience by anthropogenic disturbance (Stylinski & Allen, 1999). Options for acquiring land for nature reserves are rapidly declining, especially in those areas most in need of conservation (Trinder-Smith *et al.,* 1996).

As a signatory to the 1992 United Nations Conference on Environmental and Development

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(UNCED), South Africa is bound to protect its indigenous biota by setting aside adequate protected areas and restoring key sites (Anonymous, 1997, DEAT). However, in a political situation that favours social development needs above conservation needs, it is important to maximise the conservation value of the land available for this purpose (Holmes & Richardson, 1999). Cairns & Heckman (1996) described the situation well, by stating: "Restoration ecology requires approaches that integrate ecology and environmental sciences, economics, sociology, and politics".

This review will discuss some of the theoretical principles to consider and current methods that could be used for rehabilitation in the Succulent Karoo of South Africa with special reference to strip-mined areas. Rehabilitation can be defined as the return of some of the aesthetic and functional properties of the system, by re-landscaping and re-vegetating it (Whisenant, 1999). It is likely, that if ecological principles are followed, the outcome of restoration, in terms of the establishment of populations (Primack, 1993), communities and ecosystem functions will be more successful and sustainable in the long-term (Lockwood, 1997) yielding positive implications for all aspects of biodiversity conservation.

Although I focus on the Succulent Karoo, the concepts reviewed may be usefully applied to other arid winter rainfall areas. In arid systems constraints are such that the revegetation goal is usually to restore as many aspects of natural vegetation as possible. To do this we need to know what natural vegetation in this system looks like and how it works (Eccles & Desmet, 1999).

I will review the relevant literature under the following main headings: Surface mining methods, Aims of rehabilitation, Recruitment dynamics, Community structure, Practical issues in rehabilitation, and Economic and Managerial constraints, and then draw conclusions on general principles and the rehabilitation techniques most likely to succeed in arid winter-rainfall regions.

Surface Mining

The mining method is quite complicated and will vary with the type of material being mined, natural conditions in which the material is located, and the type of equipment available for use (Law, 1984). Surface mining includes removal of vegetation, soils, glacial drift, shales and rock overlying the deposit that is to be mined (Harley, 1976). Disturbance of the soil profile and compaction results in environmental degradation of the site. The main methods of surface mining are: 1.) open pit; 2.) opencast or strip; 3.) auger; 4.) hydraulic and 5.) dredging. (Harley, 1976; Reuter, 1997).

In this review the focus will be on strip-mining, a type of surface mining as mentioned above (see also The mining method, Chapter 1). The mining method will not be discussed in further detail, although it is also a factor that should not be neglected in the rehabilitation procedure. Use of the correct or perhaps modified methods could significantly reduce the impacts of mining on the environment.

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Aims of rehabilitation

Sustainable development is a term widely used. A definition of sustainable development would be development that aims to meet the needs of society today, while conserving ecosystems for the benefits of future generations. Good planning and environmental management will minimise the impacts of mining on the environment and will help preserve diversity. Mining is a temporary landuse, which should be integrated with, or followed by a defined future landuse. Rehabilitation is the process used to repair the impacts of mining on the environment and revegetation of the degraded area (Whisenant, 1999). The most important rehabilitation goal must be to achieve revegetation of the degraded area. The degraded areas can be converted into productive croplands by topsoiling, fertilising, seeding and if necessary irrigating. In arid systems, like the Succulent Karoo the scarcity of water and the nature of the soil generally make conversion to croplands economically and practically impossible. The most common post-mining landuses in these areas are for tourism and conservation or as rangelands for stock farming (Eccles & Desmet, 1999).

The rehabilitation of a damaged ecosystem to a functional ecosystem requires a thorough understanding of how the stable, mature ecosystem functions and maintains itself (Holmes & Richardson, 1999; Tongway & Murphy, 1999; Whisenant, 1999; Bellairs & Gravina, 2000; Bradshaw, 1997). The long-term objectives can vary from converting an area to a safe and stable condition, to restoring the pre-disturbance conditions as closely as possible with all the area's environmental values intact, which depends on the characteristics of each site (Torbert *et al.*, 1990; Ward, 1995; Bellairs & Davidson, 1999). One logical aim of rehabilitation would be to re-establish some or all of the links that control processes involved in energy and matter flow through the ecosystem. Rehabilitation to a low maintenance landuse, which is sustainable in the long term, would require an understanding of concepts of soil development, plant successional processes, species diversity and how organisms form linkages that affect important processes (Holmes & Richardson, 1999; Tallentire & Jefferies, 2000). Rehabilitation should be aimed at accelerating these basic processes to be able to form a stable system. It is debatable whether all components of biodiversity are essential for maintaining ecosystem function, at least those functions that are generally considered important from a human perspective, in the short term (Holmes & Richardson, 1999). If one looks at the high level of diversity of succulent plants in the Succulent Karoo you could argue that some species are "redundant" and need not be replaced in a rehabilitation project in order to maintain an important function or service. The degree to which links need to be repaired, and natural functioning re-instated, depends on the aims of the rehabilitation and the extent of transformation. It is however important to keep at least the most important functional groups of the particular system. Long-term resilience would be promoted by reintroducing as many

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species as possible within each functional guild (Holmes & Richardson, 1999). If the land cannot be restored to its previous use, one could become quite creative and think of other landuses for perhaps a greater overall community benefit (Harley, 1976; Ward, 1995). Golf courses, football pitches, highways and woodland walks are just some of the ideas that mining companies have come up with (Harley, 1976). The aim should be to progressively rehabilitate an area and not to wait until only after the mining has been completed (Brearly *et al.*, 2000).

Recruitment dynamics

Seed dispersal

Seed dispersal in the Succulent Karoo is generally facilitated by wind and water (Milton & Dean, 1999). This contrasts with forests where dispersal by birds and mammals are more common (Foord *et al.*, 1994). In many arid areas of South Africa, wind is a major factor to contend with when rehabilitating an area, it does not only facilitate seed dispersal as mentioned, but could also negatively influence vegetation establishment. Strong winds blow the soil away from the seedling roots and results in root exposure. Blowing sand also damages the vegetation. Windbreaks can significantly enhance the local deposition of tree and shrub seeds by attracting seed-dispersing birds from nearby undisturbed areas and also protect seedlings from the negative effects of the wind (Harvey, 2000). Birds are of minor importance in the Succulent Karoo – but far more important in the adjacent coastal thicket (Strandveld).

The long-term persistent nature of soil seed banks (ephemeral species mostly) in the Succulent Karoo emphasizes the importance of retaining the topsoil and it is therefore very important that clearing and soil stripping should take place after seedset. Species representing guilds without long-term persistent soil seed banks with poor dispersal mechanisms may need to be reintroduced to the site, depending upon the extent of transformation. Species with seeds supplied in topsoil or dispersed onto the site by wind or fauna do not need to be supplied when seeding for rehabilitation purposes. Species that propagate vegetatively or reproduce quickly by seed can be supplied at lower densities (Bellairs & Gravina, 2000). When a reclaimed site lies within a relatively intact natural landscape, little or no intervention may be required beyond site preparation (Robinson & Handel, 2000). When rehabilitating, the species' regeneration ecology should also be kept in mind if recruitment and establishment are to be maximised (Holmes & Richardson, 1999).

Seedbanks

Seeds are concentrated in the surface layer of topsoil, sometimes just in the surface few centimetres. Seed densities at Goegap Nature Reserve in Namaqualand, South Africa, were highest (41 000 m^{-2}) in sandy bottomlands, dominated by annual plant assemblages and lowest

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(5000 m^{-2}) on ridge tops with scattered perennials and few annuals (Van Rooyen & Grobbelaar, 1982). The identification of seed dormancy mechanisms and ways to alleviate these have been a major focus to re-introduce endemic plant species. Germination of seeds of annual and pauciennial succulents often shows seed dormancy mechanisms, whereas germination of perennial succulents rarely show seed dormancy (Von Willert *et al.*, 1992). Clearing, grubbing and physical removal of topsoil is not a natural disturbance to which the endemic plant community has adapted, therefore seeds need to be added to the system after mining. Knowledge of seed dormancy mechanisms and how to break these is therefore very important to ensure the germination of the sown seeds.

Germination and seedling establishment

A feature in the Succulent Karoo is that many plants occur in multispecies vegetation clumps, it does however not seem important, which species grow together. The reasons for these patterns are also most certainly related to dispersal mechanisms and differential survival of plants in protected and exposed sites. The benefits to individual plants could be that plants are protected against grazers and strong winds. The clumps also offer seedlings shade and protection against winds and therefore most germination also occurs under these clumps. Higher soil temperatures and higher wind speeds mean more water stress for seedlings in the open, whilst the air humidity within a plant canopy is likely to be slightly higher than in the open because of transpiration from the canopy. These factors all contribute to a favourable microclimate under plant canopies (Eccles & Desmet, 1999). Soil fertility also builds up under canopies, creating fertile islands, which may sustain plant productivity (Danin & Gaynor, 1997). The effects of aggregation in favourable microsites outweigh the effects of competition among these plants.

Differences in the germination of seedlings are related to seed size, shape and exposure of each microsite; physiological requirements of each species for seed germination, seedling emergence, survival and plant establishment and the effective environment present on each microsite each year (Eckert *et al.,* 1986). Neighbouring adults and juveniles of the same or different species seem to have positive impacts in some instances and negative in other (Fowler, 1988). Tielborger & Kadmon (2000) has shown that the positive effects of shrubs on understorey should dominate in years when water is not the limiting factor, due to the favourable nutrient status under the canopy, compared to the open areas. In years where water is the limiting factor, the competition for water due to rainfall interception by shrubs is higher than the facilitative effect of the shrubs. Therefore, the balance between competition and facilitation would depend mostly on the moisture availability of the physical environment. Eccles *et al.* (1999) however has shown that the interactions between plants in the short strandveld and medium strandveld communities range from neutral to weak positive interactions. They have assumed that if the medium strandveld are longer-lived, the interactions of plants are likely to develop over a longer time period. At a later stage,

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Eccles *et al.* (2001) argued that the net interactions between adult plants would be neutral, but at other life stages (e.g. the seedling stage), stronger, positive interactions would occur. These interactions would over evolutionary time result in preference to clump.

Disturbance

The arid, winter rainfall region of the Succulent Karoo is rich in minerals deposited by evaporation and igneous activity. These minerals are usually strip-mined which results in the destruction of the overlying vegetation (Milton & Dean, 1999).

On a post-mining landscape, where there is no vegetation, seeds are unlikely to be deposited; they will just blow away (Eccles & Desmet, 1999). Soils are affected as they are either removed or relocated, thus being damaged in the process, or are buried under tonnes of waste rock. In all cases, soil structure is changed, useful soil biota such as vegetative propagules and fungi can be permanently lost, and nutrient quality decreases (Lindbeck, 1999). Destruction of the vegetation will also lead to lower levels of available phosphorus and total nitrogen (Brown *et al.,* 1999). Surface mining practices and the absence of environmental protection measures in India and also in many other countries, have caused the destruction of land resources, i.e. denudation of vegetative cover, creation of grossly uneven topography, depletion of water resources, loss of soil and fertility, surface crusting and soil erosion, etc. The use of surface mining techniques in South Africa has made the public and regulatory authorities very aware of such environmental impacts (Rethman *et al.,* 1999). Rehabilitation of such degraded desert sites is a challenging task due to the harsh environmental conditions and the lack of suitable technology (Sharma & Gough, 1999).

Community structure

Diversity and Endemism

The Succulent Karoo has a rich succulent flora. There are 3700 species from 32 families, which constitute over a third (32%) of the world's total of succulent plants (Van Jaarsveld, 1987). Some families, for example Mesembryanthemaceae and Zygophyllaceae are found mainly in the Succulent Karoo biome (von Willert *et al.*, 1992). Although succulents are found in other regions of the world, they do not have the same species richness or constitute such a high proportion of the flora (Milton *et al.*, 1997; Milton & Dean, 1999). Succulence can be defined as plants that have tissues that can store water for later use (von Willert *et al.,* 1992). The degree of succulence can vary considerably. Different organs such as leaf, stem, root or combinations thereof, may be succulent. Succulents also vary in growth forms e.g. creeping and erect. The predominance of succulents in semi-arid regions is most commonly attributed to their ability to absorb water during times when water is plentiful, and to store this for use in times of drought. This is based on the correlation between succulent abundance and low rainfall (Ellenberg, 1981; von Willert *et al.*,

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1992).

There are specific ecological conditions that seem to favour the dominance and diversity of succulents in regions such as the Succulent Karoo: Succulents predominate in regions of low but predictable rainfall (Milton *et al.*, 1997; Milton & Dean, 1999) and occur in areas where the summer temperatures do not exceed 32 ^{0}C and winter not below 0 ^{0}C. They survive high temperatures by adopting structural modifications such as self-shading and reduction of surface area orientated towards the sun (von Willert *et al.*, 1992). These structural modifications of succulent plants and their ability to survive under harsh environmental conditions, makes them well suited for translocation during rehabilitation.

Succession

Skousen *et al.,* (1994) stated that vegetation of abandoned mined land passes through three stages. Firstly, rapid colonization of microsites by plant propagules from the surrounding undisturbed land that forms small islands of vegetation. Then the existing patches grow in size with only a few new islands establishing. Lastly the patches coalesce.

The ultimate goal in most rehabilitated areas is to assure succession in the ecosystem so that vegetative cover and nutrient cycling will approach a condition stable as that in the pre-mining environment (Sorensen & Fresquez, 1991).

Landscape Pattern

Indications are that nomadic pastoralists were present during the last two millennia in the Succulent Karoo. Little is known about the impact these people had on the vegetation. European farmers started moving into the region during the seventeenth to nineteenth centuries. Boreholes enabled farmers to settle in previously inhospitable environments. The first records that warn of degradation of the karoo date from this time (Cowling & Pierce, 1999).

A knowledge of disturbance history as well as current status is essential in predicting which components of a community are likely to have been lost and in need of reintroduction. It is important to take edaphic variations and other environmental gradients into account when selecting species and ecotypes for addition to a community. Disturbance of arid shrublands may disturb successional processes, resulting in permanent landscape change (Okin *et al.,* 2001). Some authors argue that vegetation changes are irreversible because of the time required to reverse them (Illius & O'Connor, 1999). This view could have significant impacts when managers have to make decisions on what their aims would be for rehabilitation. Rehabilitation results in higher costs for mining companies and these expenditures would be wasted if the disturbance due to mining cannot be reversed in some way.

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Practical issues in rehabilitation

As mentioned before, to restore vegetation in arid environments is an extremely slow process. These areas are limited not only by soil moisture, but also cannot economically support intensive or costly revegetation practices (Abu-Irmaileh, 1994). Mining is economically important in that it is a provider of employment and training for local people (Milton, 2001), since Namaqualand has low agricultural potential and generates little income per hectare (Milton, *et al.*, 1997). On the other hand, a large part of the income of the area is generated through ecotourism and therefore the unsightly mined areas should be restored to ensure ongoing income through ecotourism. A mine area rehabilitation plan should make logical and effective use of natural resources available in the region, such as precipitation, topography, topsoil, soil amendment material, and locally adapted plant species. It also should be cost-effective (Sharma & Gough, 1999).

Topsoil and Mine spoil

Pre-mining overburden analysis can be very valuable, but the influence of pedogenesis processes should be kept in mind when attempting to predict the eventual chemical and physical properties of the resulting mine soil. The properties of newly constructed mine soils cannot be viewed as static (Haering *et al.,* 1993). It is also very important then to conduct post-mining soil and spoil inventories that anticipate potential rehabilitation problems (Rethman *et al.*, 1999; Sharma & Gough, 1999).

Topsoil is one of the most important factors in rehabilitation (Le Roux & Odendal, 1992). It contains the majority of seeds and other plant propagules, soil micro-organisms, organic matter and more labile plant nutrients (Law, 1984; Low *et al.,* 1999; Reuter, 1997) and serves as a rooting medium that should result in rapid and vigorous vegetation cover (Chong *et al.,* 1986; Le Roux & Odendal, 1992). A layer of vesicles just below the surface is often found in dry-land soils. These vesicles are spherical voids of up to a few mm in diameter. During and after rain the uppermost part of the regolith develops a surface seal, trapping air, which is compressed, and which may also expand due to solar heating. Such layers could stop water from penetrating the soil. The formation of these vesicles requires a surface seal of some sort, for example, surface gravel layer or hard soil surface crust. A surface seal is often found on mine spoil due to compaction or high sodium content. The presence of a well-developed vesicular layer can provide a basic level of understanding about how a site will respond to rainfall and could therefore act as an indicator of certain geomorphic processes. It could also provide qualitative information on the amount of runoff and erosion that is likely to occur (Brown & Dunkerley, 1996).

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Nutrient cycling

Successful vegetation after mining will depend upon the re-establishment of nutrient cycling. It is known that a deficiency of N limits the establishment of vegetation on many mine spoils and that long-term rehabilitation success depends on the reestablishment of an organic N pool and N cycling. Nitrogen accumulation occurs only in the top 0mm to 50mm in mine spoils (Sorensen & Fresquez, 1991; Li & Daniels, 1994). Soil micro-organisms, including arbuscular mycorrhizal (AM) fungi, play a significant role in nutrient cycling in any ecosystem through their influences on carbon and nitrogen cycling, mineralisation and immobilization of plant nutrients and production of stable organic matter through their physical relationships with higher plants (Peterson *et al.,* 1985; Ward, 1995). Surface mining leads to removal of growing plants, soil disturbance and soil storage which in turn results in lack of sufficient resident microflora including viable propagules of AM fungi (Rao *et al.,* 1996; Bellairs & Davidson, 1999). There are many circumstances where a number of nutrients, including N, P and K, are not present in sufficient quantities in the mine over-burden material (Mcginnies & Nicholas, 1980; Davies *et al.*, 1995; Rao *et al.,* 1996). Low levels of these essential plant nutrients will affect plant growth (Khresat *et al.,* 1998). Red colouration in the foliage of plants would be one of the signs of deficiency due to a lack of phosphorus that one would be able to identify (Mikli *et al.,* 2000). Although microbial activity is low in gypsum mine spoil it can be increased through introduction of plants. Growth of most of the selected plant species in gypsum mine spoil was equal to or more than that observed in normal soil (Rao & Tarafdar, 1998).

Cations, particularly Na tends to leach fairly rapidly in newly formed mine soils but leaching slows down as the soil settles. This is a result of the exposure of fresh mineral surfaces and the formation of large macropores after disturbance. After the soil settles the leaching of cations slows.

Soil stockpiling

In the case of mining operations, the stockpiling process involves removal of the topsoil layer and any other soil layers necessary to get to the substance that is being mined. The topsoil is removed first and stockpiled in one pile and the soil layer below is also removed and stockpiled separately. This subsoil layer is referred to as the overburden. Stockpiles are often meters deep and soil stays in these stockpiles for varied time periods, depending on the situation at each site. When mining operations are complete, the overburden material is reapplied and levelled and then the topsoil is replaced and spread over the overburden, to provide a planting medium. This process involves the use of heavy equipment (Strohmayer, 1999). Motor scrapers operating on a circuit usually lift topsoil. These machines are capable of removing a thin layer of soil to a precise depth so that nothing is wasted. Fairly dry conditions are needed to achieve this. It is inevitable that the handling of overburden and the movement will create dust over stripped areas. Every means should be required to suppress the dust for example the use of water bowsers (Harley, 1976).

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Changes in soil during storage

Aggregate structure breaks down as successive layers of soil are removed and stockpiled elsewhere when mining begins (Galajda, 1999).

An increased bulk density, decreased water holding capacity, chemical changes, reduced nutrient cycling, reduced microbial activity, and loss or reduction of viable plant remnants and seeds are changes that occur when soil is stored (Harley, 1976; Conners & Bainbridge, 1994; Davies *et al.*, 1995; Shroeder, 1995; Lindbeck, 1999; Rethman *et al.*, 1999; Strohmayer, 1999; Samaraweera *et al.,* 2000; Galajda, 1999). It has also been shown that stockpiled soil that has been re-spread is restrictive to water movement, (Davies *et al.*, 1995) further inhibiting air movement and bacterial growth. The surface could become as hard as a crust in summer and waterlogged in winter, during which the soil temperature will be lowered, resulting in late growth the following spring (Harley, 1976). Strohmayer (1999) has shown that the storage of soil has less adverse effects, as long as care is taken to minimize compaction and mixing of subsoil and topsoil. It has also been shown that the soil pH and mineral content of stockpiled soils are not affected, as long as the stockpiles are not too deep (not more than 1m) or stored for long periods of time (less than 3 months). Soil biology also bounces back quite quickly once the soil is re-spread (Strohmayer, 1999). Soil, which is stockpiled more than a meter deep undergoes chemical changes, such as the accumulation of ammonia and anaerobic conditions that, occurs at the base of the pile (Davies *et al.*, 1995). Detrimental biological effects also include absence of propagules and decrease of viability of buried seeds as well as heavy losses in microbial community and decreased nutrient cycling (Ashwath *et al.,* 1999; Low *et al.,* 1999; Strohmayer, 1999).

Harley (1976) states that soil will be acid and short of nitrogen (Li & Daniels, 1994) and phosphates and also lifeless and without structure, if stored in dumps for several months. Age of topsoil is particularly important for revegetation purposes, because many of the biennial and annual plant seeds naturally present in the topsoil remain viable for only a limited time. After storage of only 4-6 months, germination could decrease greatly (Low *et al.,* 1999).

Soil takes centuries to develop from parent material and organic matter. Stockpiling and the subsequent reapplication of the topsoil, allows for planting conditions that are closer to the pre-disturbance condition than planting on the subsoil layers that remain (Rethman *et al.*, 1999; Strohmayer, 1999). When replacing the overburden, one should aim to create an area, which is self-draining. Rooting the overburden will break the hardpan of clays crushed by the motor scrapers engaged on levelling and permits the penetration of surface water (Harley, 1976).

The removal of vegetation and exposure of bare soil to the weather has an adverse effect through changes in soil temperature regime. The humus of the topsoil disappears while the impacts of raindrops and of trampling by livestock are much greater on the bare soil surface (Thurrow, 1991). The result is a highly compacted concrete-like character, also referred to as

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sealed surface. Infiltration rates are low and surface runoff is thus high. It is very difficult for seed to lodge, germinate and establish on such a surface (Chong *et al.,* 1986; Mnene *et al.,* 1999). The new soil profile after mining will often be a mix of subsoil and topsoil and below that would be the large gravel and boulders (Lyle, 1987; Shroeder, 1995; Samaraweera *et al.,* 2000). In some areas waste rock weathers rapidly to form suitable materials for revegetation (Ward, 1995). McGinnies & Nicholas (1980) found that there was no particular advantage or disadvantage to mixing topsoil with spoils of coal mines.

Replacement of topsoil and amelioration

Initially most of the soils on rehabilitated surface mines will have no structure. Moving soil from one place to another and the grading process will result in compaction by the equipment used and the destroying of the structure of the original soils (Lyle, 1987). Revegetation on the coast of northern Namaqualand near Kleinzee has shown that of all the different methods used, that covering by topsoil is by far the most effective and probably the most cost-effective treatment (Fey, 1996).

When replacing topsoil, it is often found that subsoil rock fragments are present. These rock fragments, depending on their size, could be considered as natural soil surface stabilizers. A cover of rock fragments could protect the soil against the impact of raindrops and flow detachment, reduction of physical degradation and retardation of physical flow velocity (Poesen *et al.,* 1994; Poesen & Lavee, 1994; Fey & Kruger, 2000). Rocks could also act as a mulch, resulting in lower evaporation losses. The lower temperatures underneath the rock fragments during the heating period, as well as the moisture accumulation can be of significance to seedlings and fauna in dry and hot periods or areas. The presence of rock fragments in the soil will also reduce compaction by acting as a skeleton. These factors due to rock fragments will reduce the intensity of physical degradation in fine textured soils. In general it could be stated that rock fragments would be more beneficial in clay soils with deep rooting shrubby plants (Poesen & Lavee, 1994). Bochet *et al.* (1998) found that a cover of gypsum fragments would have the same effects as the rock fragments.

It is important to screen topsoil for effects like subsoil clays, that could be dispersive or pore clogging or sandy topsoils that are non-wetting. Mine spoil sodicity causes clay particles to become dispersed, reducing the pore size and restricting movement of air and water. Upward migration of Na can deteriorate the quality of the overlying topsoil or subsoil and contribute to declining productivity (Oddie & Bailey, 1988). Rapid drying of the soil surface in arid areas results in a crust trapping emergent seedlings (Bellairs & Davidson, 1999). Appropriate amendment should be taken when planning soil profile reconstruction (Bellairs & Davidson, 1999; Smettem *et al.,* 2000). The soil surface should be modified to improve water infiltration and seed germination to enhance the productive capacity of pastures (Lorimer, 1999). Topsoil and subsoil are often replaced at different depths from the pre-mined conditions, due to grading operations but this does not affect the water yields on reclaimed mined lands in relation to unmined areas in a semi-arid

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climate (Schroeder, 1995; Halvorson *et al.,* 1987).

In saline conditions gravel and gypsum filling of shrinkage cracks of gold ore slurry could facilitate the leaching of salts out of the residue (Bell *et al.*, 2000; Pratt *et al.,* 2000). The use of gypsum and organic matter to treat high sodicity and salinity levels are recommended (Milton & Dean, 1996; George & Bell, 2000) and for amelioration of the poor physical structure of the material (Bochet *et al.*, 1999). The surface application of gypsum does not only ameliorate high sodicity and salinity levels and poor soil structure, but also indirectly improves the productivity of the vegetation (Schuman *et al.,* 1994; Warren, 1989). An application rate of 5 tonnes per hectare is normally used, but for clayey subsoils 10 tonnes/hectare may be required (Warren, 1989). Under semi-arid conditions where precipitation was less than optimum, responses to P fertilization are less likely (Halvorson *et al.*, 1987). When replacing topsoil the pre-mining landscape must be restored as close as possible. Site-specific controversies often occur over the subjective evaluation of how much deviation from the approved topography may occur in the actually constructed topography. There are also arguments to replace variable depths of topsoil in order to establish more diverse post-mining plant communities and higher-quality wildlife habitat (Giurgevich, 1999).

When replacing topsoil compaction can be minimized by using a mining wheel rather than scrapers to dig stored soil. Transporting could be done with a conveyer belt with trundling action, which improves soil structure, by breaking up massive aggregates. Use of bulldozers should be minimised (Galajda, 1999).

Many types of soil amelioration result in very high rehabilitation costs and fairly low success rates in arid areas for example watering, fertilizers and non-indigenous plants (Milton, 2001). They would therefore not be feasible as an option for strip-mine rehabilitation and will not be discussed any further in this review.

Vegetation

Species selection, transplanting and facilitation

Successful rehabilitation of strip-mined sites requires selection of suitable plant species (Law, 1984; Warren, 1989; Abu-Irmaileh, 1994; Van Rensburg *et al.,* 1998), modification of the soil at the planting site and in situ water harvesting techniques. It is difficult to establish any vegetation on such sites due to harsh environmental conditions in arid areas and because revegetation of mine spoils poses the problem of adaptation of plants to the unusual soil conditions (Rao & Tarafdar, 1998; Pieterse, 1999; George & Bell, 2000). Parameters such as physical components of the soil profiles and seasonal conditions appear to be critical in determining the resultant species assemblages that occur on a particular rehabilitation area (Samaraweera *et al.,* 2000).

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There are many advantages of using local indigenous species for the rehabilitation of disturbed land (Rethman *et al.*, 1999). The use of these species on a mined area would result in the development of plant communities that are self-sustaining over the long-term and would result in a more diverse plant community with greater stability and a greater variety of habitats to wildlife than would exotic species. Many exotic species are not as long-lived in arid and semi-arid environments as adapted indigenous species. Indigenous species would also be the best choice to facilitate succession and from an aesthetic point of view (Redente & Keammerer, 1999).

A stable landform and growing medium would be one of the initial requirements for the establishment of native vegetation in many habitats (Bellairs & Davidson, 1999). Only plant species that have evolved through natural selection and have become adapted to specialized environments can colonize such sites. Studies, done in the Indian Desert on gypsum mine spoil, have shown that the mine spoil supported significantly higher growth of *Prosopis juliflora, Salvadora oleoides* and *Cenchrus ciliaris* compared to normal soil (Tarafdar & Rao, 1997). Concentrations of phosphorous, potassium and calcium in plants growing on gypsum mine spoil were higher than observed in normal soil. In general, concentrations were lower in all the plant species growing in normal soil. Tarafdar & Rao (1997) observed 31 different herb and shrub species growing naturally on gypsum mine spoils also in the Indian arid zone and all were found to be infected by AM fungi. AM fungi are considered as vital components in the restoration /revegetation of degraded sites (Tarafdar & Rao, 1997).

The most effective way to initiate natural recruitment is to transplant some established plants onto the post-mining surface. The presence of established plants would provide appropriate microclimates for recruitment and reduce the exposure of recruits to various sources of risk. Soil associated with the translocated plants is a potential source of mycorrhiza and soil fauna, and translocated plants that establish and set seed replenish the soil-seed bank. If planted in the correct arrangement and density, transplants will provide the necessary seed trapping function (Eccles & Desmet, 1999). Transplanting plants could have different success rates in arid areas, depending on the rainfall for that particular year. Watering transplanted species during drought could result in green foliage on some species and would attract more wildlife, which would browse these plants and negatively influence their survival. The green foliage would also result in higher evaporation losses from the plant, which would also reduce their probability of survival. Transplanting may only be feasible where only a few plants are needed (Martin *et al.,* 1999). Thick-leafed succulents would respond best to transplanting in the Succulent Karoo (Fey, 1996).

Shrubs could represent islands of fertility and nutrient accumulation in shrubland ecosystems (Schlesinger & Pilmanis, 1998). It is found that under shrubs the soil has a lower bulk density and penetration resistance but a greater aggregate stability.

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A favourable microclimate is created in terms of solar radiation, wind speed, soil temperature and evaporation rates (Bochet *et al.,* 1999). Some surface-soil microsites act as safe sites for seed germination, seedling emergence, seedling survival and plant establishment. If this is the case revegetation by desirable species and secondary succession will be greater (Eckert *et al.,* 1986). In the deserts of Uzbekistan a local microclimate between established belts of shrubs are created which ensures favourable conditions for the growth of other plant species (Reizvikh, 1999). Desert annual plants often prefer areas under the canopy of shrubs. The importance of such facilitation would increase with increasing abiotic stress, therefore, relatively dry years would result in limited growth of annuals under shrubs due to competition for water, while relatively favourable years would result in positive effects of shrubs on the annual understorey, due to higher nutrient contents under shrubs (Tielborger & Kadmon, 2000). Adult plants in an arid system simultaneously experience both positive and negative interactions with other plants. Over an entire lifespan of individuals the net interactions would be positive, otherwise plants would not naturally occur in clumps as they do in arid systems (Eccles *et al.,* 2002). One could also argue that presence of a surviving neighbour would indicate that a spot had been favourable for seedlings (Fowler, 1988).

Seed collection and seeding

Seeds from undisturbed areas could be harvested by hand-harvesting or suction harvesting. The seeds can be harvested from canopies of particular species or from litter on the ground, but care should be taken to do the harvesting only when the seeds are ripe. Seeds should be stored in paper or canvas bags in a cool, dry environment and dusted with insecticide (Holmes & Richardson, 1999). The seeds could then be used at the appropriate time.

Alien invasive species

Alien plant species that colonise disturbed sites in arid areas are often those that originally evolved in environments similar to those of the host country, and have effective seed dispersal mechanisms, high seed production rates, local availability and are tolerant of minespoil conditions (Skousen *et al.,* 1994).

The most important alien invader species in the Succulent Karoo are *Prosopis* spp., *Salsola kali, Atriplex semibaccata, A. nummularia* and *A. lindleyi* (Milton & Dean, 1991). *Atriplex* species (also known as salt bushes) provide an adequate N supply for ruminants (Lailhacar *et al.,* 1999) and they are known to be drought- and salt- tolerant forage plants (Howeizeh & Salehi, 1999; Jafari & Khalkhali, 1999; Osborne *et al.,* 2000). They also provide a high surface cover and a large amount of palatable biomass (Jafari & Khalkhali, 1999). In South Africa the use of *Atriplex* species as forage crop in arid, saline conditions is still a very controversial and unresolved issue. Saltbushes store salt in bladder cells on their leaf surfaces and falling leaves may increase surface

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soil salinity around the plants, enabling them to compete successfully for space with less salt-tolerant plants (Milton & Dean, 1999). *Prosopis* spp. are known to tap water at considerable depth and therefore can out compete many of the local spp. They are also known to have a very durable soil-stored seedbank (Milton & Dean, 1999).

The herbaceous *Atriplex semibaccata* and the shrub *A. nummularia* are used to cover soils disturbed by strip-mining in Namaqualand (Succulent Karoo) (De Villiers, 1993). However, there is little evidence that these species facilitate the establishment of indigenous vegetation (S.J. Milton, personal communication). These invading species could therefore hinder the rehabilitation process moreover, they do not assist in reaching the goal of restoring the species rich vegetation of the Succulent Karoo.

Microsites

At the size-scale of most seeds, the soil surface on which they are dispersed is highly heterogeneous and that this heterogeneity of the soil is likely to provide microsites offering widely different conditions for germination. It has been shown that microsites, located at a distance of not more than 100mm differ dramatically in their temperatures, which has significant effects on germination (Gutterman, 1997). Micro-topography exerts its effects through modifying seed-water relationships (Harper *et al.,* 1965). A suitable seedbed should provide numerous microsites for the favourable establishment of seedlings (Law, 1984).

Micro catchments

Waterharvesting is a method of exploiting available precipitation and is practised in many arid and semi-arid regions for both economic and environmental reasons (Fidelibus & Bainbridge, 1994). The use of catchments is highly recommended for restoration projects undertaken in the deserts of California and the southwestern United States, since it has been proved that the overall survival of shrubs inside catchments after one year was 83 % versus 64% outside. A study in Kenya has shown that when pits were dug in an area and seeds liberally sown, there were no seed establishments between pits. The hard surface inhibited penetration by roots of germinating seeds. It was observed that most of the seeds were washed or blown into the pits (Mnene *et al.*, 1999). Regardless of the season post-treatment herbage were only able to establish in the pits (Mnene *et al.*, 1999). In the Negev desert it was found that desertification could be reversed by adding human-made pits and mounds to arid and semi-arid landscapes (Boeken & Shachak, 1994). In the Tanami Desert of central Australia, areas where topsoil was ripped into the waste rock, revegetation was generally good. Growth was especially good on furrowed banks suggesting that these surfaces were particularly conducive to seedling establishment. The rough surface provides shelter from the wind and sun for emerging seedlings and also encourages maximum water

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infiltration (Skousen *et al.*, 1994; Low *et al.*, 1999). Other rainwater harvesting techniques used were micro-catchments, half-moon terraces, teardrop configurations and inward sloping bench terraces. Half-moon terraces, followed by micro-catchments and ridge and furrows were the most successful in experiments done on gypsum-mined surfaces in North-west India (Sharma & Gough, 1999). In Cholistan (part of the Great Indian Desert), natural depressions collect water, which plays a large role in the development of rangelands and supports grasses and legumes as supplementary fodder (Ahmad, 1999). The microclimates, water harvesting, nutrient pooling from areas of runoff to areas of run-on, and suitable seedbeds are very important in arid regions (Bellairs & Davidson, 1999). It was observed that for fast vegetation establishment, site preparation was very necessary (Mnene *et al.*, 1999).

Rock fragments and litter

Fowler (1986) has shown that litter and rocks and not the proximity of an adult plant, increased germination, survival and growth. A litter layer also plays a significant role in the improvement of soil structure, reduction of erosion, enhances infiltration and reduces compaction due to raindrops (Bochet *et al.,* 1998). A safe site for the three dominant grass species that she used seems to be a microsite that prevents desiccation. She has also shown in 1988 that aggregation in favourable microsites outweighed the effects of competition. The presence of nearby rocks improved survival of seedlings and is perhaps due to the shading of the soil and the reduction in evaporation. If soil contains gravel or stone fragments these will also contribute to the surface residue and eventually limit the crusting process by forming a protective mulch against raindrop impact. In semi-arid climates this protective mulch will enhance water availability and stimulate vegetation recovery, which in turn will reduce erosion (Law, 1984; Fey pers comm., 2000). Litter has been shown to increase seedling survival in arid environments.

Evaluation of restoration actions

Assessment of the progress of rehabilitation should be made soon after initiation of rehabilitation activities, and rehabilitation areas should be frequently monitored to assess the success of various techniques. Early assessment obviates unnecessary expenditure on unsuccessful methods. Monitoring also enables mining companies to determine when the rehabilitated area has recovered to the level required by law. Ascertaining timely rehabilitation success is critical because: a.) There will be limited opportunity to address serious errors in this evaluation, b.) Because mining companies would want to return the mined areas to the land management or government agency responsible for them and c.) To obtain the bond funds they placed in escrow to ensure that rehabilitation was accomplished. Success is also important because the loss of our natural

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resource base and the economics of correcting rehabilitation failures can have extreme consequences to the region, country and possibly the world. Audits provide opportunities for the evaluation of projects by independent observers within the context of site environmental management systems (Fox & Jan, 2000). Monitoring techniques should be designed to provide statistically valid results with the desired order of accuracy (Ward, 1995) for use in audits.

The ecosystems functional analysis (EFA) approach appears to have potential for practical application by such regulators (Ludwig & Tongway, 1997). Tongway and Murphy (1999) have proposed the trigger-transfer-reserve-pulse framework as a conceptual basis for the landscape function analysis methodology, fully described in Ludwig & Tongway (1997). This monitoring system assesses minesite ecosystem development from the very early stages using indicators as the information source. It has the potential to mesh with both the technical planning phases and societal value aspects of rehabilitation and become an integral part of the whole process of rehabilitation. The periodicity of assessment and the nature of the data and information can be arranged to provide appropriate and timely inputs to the successful management of minesite rehabilitation (Tongway & Murphy, 1999).

Invertebrates play an important role in the structure and maintenance of ecosystems, being fundamental to processes such as decomposition, herbivory, parasitism and pollination and forming important dietary linkages throughout the food chain. They are therefore important organisms to include when considering rehabilitation success following mining (Majer, 1997). Ants are the dominant faunal group throughout the arid zone. Because of their abundance, diversity and functional importance in natural ecosystems, it has been suggested that ants are the ideal faunal group to use as bio-indicators to evaluate restoration programs (Ward, 1995). Increases in soil microbial biomass tend to parallel increases in ant biodiversity across different aged rehabilitation areas (Anderson, 1997). In Namibia termites and tenebrionid beetles were used to derive indices of biological integrity and therefore establish the condition of the rangeland (Barnard *et al.,* 1999; Zeidler *et al.,* 1999). Spiders are also useful as bio-indicators as they interact with the environment in such a way that they can reflect ecological change (Brennan *et al.,* 2000.). Milton *et al.* (1998) has developed a plant- and soil-based guide for rangeland health assessment for ranchers in arid Karoo shrublands of South Africa. It is a practical guide that could possible be useful for the assessment of older rehabilitated minespoil.

To be able to assess the success of rehabilitation widespread agreement on certain issues are needed: what is an acceptable level of species diversity; how indistinguishable should a rehabilitated area be from neighbouring areas and many more. At this stage, rehabilitation can be considered successful when the site can be managed for its designated landuse without any greater management inputs. There should also be confidence that the restored ecosystem will change with time towards the make-up of the surrounding area. Assessment of rehabilitation

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success to date lacks objectivity, because of difficulties in integrating monitoring data and further work is needed to develop suitable methodology (Fox & Jan, 2000).

Economic and Managerial Constraints with Rehabilitation

In China, problems related to the reclamation of mined land include insufficient enforcement of environmental law, lack of initiatives of the mining companies, use of inappropriate reclamation techniques, lack of funding for reclamation and overall planning (Wong *et al.*, 2000). Some of these problems are also encountered in South Africa and recommendations should be made to rectify the deficiency in reclaiming disturbed sites.

Minesites have to contend with various limitations. The location of the ore body could be in an ecosystem, which is inherently difficult to deal with. There could also be technical and financial difficulties in the material available for rehabilitation and the recreating of the original landforms. The high cost of rehabilitation forces careful planning to avoid getting it wrong, which results in delays and expense, whilst there is no agreed set of criteria or methodology to assess completion criteria. In arid areas it is also always a problem to recommend an acceptable time frame for rehabilitation and the aesthetic values of the final appearance of rehabilitation can be very subjective. Other limitations are the uncertainty of establishing a new biological system and spatial limitations for wastes and increasing haulage costs. Lastly, it is legally binding to rehabilitate without causing offsite damage to others (Lanz, 1997).

The cost of minimising environmental impacts has to be weighed against social issues as the inevitable cessation of mining activities is approached within the next decade or two (Mackenzie & Molyneux, 1996). The most efficient level of output of mineral production will be that which maximizes the net benefit to society, assuming that this is positive (Azcue, 1999). Mining companies are now more aware that costs of rehabilitation can be greatly reduced in respect to plant establishment by the conservation of soil seedbanks within topsoil resources (Bellairs & Davidson, 1999). A problem that mine managers often have to deal with is a lack of human resources. Often personnel with specific qualifications and skills related to revegetation is required, which in return would result in higher costs to the company (Fey, 1996)

There is no doubt that mining is a necessary and essential component of Namaqualand's economy. The industry accounts for more than half of the region's gross geographic product and is its largest employer. The industry, however has, until very recently, not recognized the fact that it operates in an area of great biodiversity and that its impacts carry a cost. The tourism potential of large areas of coastline could never be fully restored. New legislation does require an assessment of the impacts that further mining operations would have on the environment as well as rehabilitation procedures (Cowling & Pierce, 1999).

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Conclusions

I would like to conclude by stating that the rehabilitation process is ongoing and cyclical. There are many factors influencing the aims of rehabilitation, such as climate, community structure, recruitment dynamics and economic and managerial constraints. When the aim of rehabilitation has been set out at a particular site, the rehabilitation process follows. This involves practical implementation, monitoring of the work completed, evaluation of what has been done and finally decision making on whether the rehabilitation is successful or if the methods could be improved. This is an ongoing and cyclical process, until the vegetation reaches a stage where it complies with the original aim of the rehabilitation at that site. See Figure 1.3 for a conceptual model of these factors and processes.

Much research remains to be done on methods of rehabilitation of mined surfaces and on processes that affect that rehabilitation (Bellairs & Davidson, 1999; Sharma & Gough, 1999). This needs to be applied research at particular sites. In Namaqualand, South Africa, there is also a need for experimentation to decide which of the many factors is the most limiting to long-term ecosystem recovery. To enable us to restore lost productivity and maintain plant species diversity, information on these limiting factors on denuded and altered soils is needed (Milton & Dean, 1999). The treatment of pristine sites to evaluate the effects of salinity and sodicity and fertilizer treatment of subsoil materials with both conventional and slow release nitrogen sources, coupled with gypsum amendment should have valuable results. Since hydrology is one of the most limiting factors in arid environments the creation of an artificial subsurface moisture barrier prior to topsoil replacement would also be worth testing (Fey & Kruger, 2000).

Aspects such as seedbed ecology, seed dormancy mechanisms and establishment requirements of native species are still unknown (Bellairs & Davidson, 1999; Redente & Keammerer, 1999; Sharma & Gough, 1999). Seed handling, collection and storage and the biology of germination pre-conditioning and sowing needs to be developed if rehabilitation is to be successful (Tongway & Murphy, 1999). For no plant community is the role of species-specific requirements for germination and establishment well understood and few communities have had the safe sites of some of their species characterized (Fowler, 1986).

Research is also needed on indicators of rehabilitation success to ensure that indigenous vegetation establishment on rehabilitation areas are successful. Very little is known about the long term success of native vegetation establishment on mined lands and the ability of rehabilitated vegetation to cope with future disturbances. Therefore, work needs to be conducted on the decommissioning of mine-sites in arid pastoral regions and on their resilience to grazing. The full impact of grazing pressure has not been properly evaluated (Bellairs & Davidson, 1999).

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Rehabilitation should be part of an integrated program of effective environmental management through all the stages of resource development, from exploration to construction, operation and closure. Mine managers in co-operation with regulatory bodies and interested and affected parties need to work together to develop successful strategies to deal with the disturbances of topography, soils and vegetation of surface mined areas in the Succulent Karoo Biome of South Africa. The development of these strategies, within an adaptive approach, would be dependant on regular monitoring to assess the degree of success over time. All personnel involved with mining operations should be committed to achieve success with rehabilitation and government should set measurable standards of rehabilitation and organize an acceptable system of monitoring.

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CHAPTER 3

SUCCESSION ON A STRIP-MINED AREA IN THE SUCCULENT KAROO OF SOUTH AFRICA

Abstract

A vegetation survey was used to establish the percentage cover, species richness, and species diversity and also to define species associations on a gypsum mined site in an arid, winter-rainfall region of South Africa. The undisturbed vegetation was sampled and compared with mined areas of different ages and different treatments. It was found that percentage cover, species richness and diversity were not necessarily related to the age since mining, but that factors such as the year that topsoil was re-spread or the treatment of the area plays a greater role in influencing these factors. As expected, all of these factors, including the species associations differed between the mined areas as a whole and the undisturbed areas. Some areas can be expected to show a large degree of recovery in the space of a few years, whilst others would show little or no recovery over a period of decades. It is important to recognise rehabilitation as a gradual process that takes place at different rates in different areas and in different years.

Key words: plant communities, rehabilitation, species diversity, species richness, strip-mining, succession

Introduction

Clements' (1916) view of succession represented an universal law that accounts for the predictable, directional change in the nature of a disturbed place and eventually leads to a stable community, termed the climax. After a change in habitat conditions or the creation of a new habitat, a sequence of species replacements occurs which leads eventually to a relatively stable state, usually called the climax. A "stable' community can, however be highly dynamic, since plants grow and die, which results in natural vegetation being a mosaic of patches at different stages of regeneration (Schütz *et al.,* 2000). Clements (1916) proposed that six basic processes function during succession, that is nudation, migration, ecesis, competition, reaction and stabilization. Nudation, the process creating a patch of bare soil, is what begins succession. Plants colonizing disturbed patches will either come from propagules (seeds, root fragments or whole plants), remaining in the soil or propagules arriving from somewhere else. Ecesis, the successful establishment of plants, is controlled by local environmental conditions.

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Competition, the battle for limiting resources that occurs among established plants, will eliminate some species and favour others. Reaction, the change of the environment as a result of the plants growing and dying, will continually change the availability of resources. Stabilization, a condition that rarely ever occurs, develops as a very long-lived species dominate a site.

In the case of strip-mining, succession can and should be an integral part of the planning strategy. Skousen *et al.* (1994) stated that vegetation of abandoned mined land passes through three stages. Firstly, rapid colonization of microsites by plant propagules from the surrounding undisturbed land or from small islands of residual undisturbed vegetation takes place. Then the existing patches grow in size with only a few new islands establishing. Lastly the patches coalesce. The ultimate goal in most rehabilitated areas is to assure succession in the ecosystem so that vegetative cover and nutrient cycling will approach a condition as stable as that in the premining environment (Sorensen & Fresquez, 1991).

A knowledge of disturbance history as well as current status is essential in predicting which components of a community are likely to have been lost and in need of reintroduction. It is important to take edaphic variations and other environmental gradients into account when selecting species and ecotypes for addition to a community. Disturbance of arid shrublands may alter normal successional processes, resulting in permanent landscape change (Okin *et al.,* 2000). Some authors argue that vegetation changes are irreversible because of the time required to reverse them (Illius & O'Connor, 1999) or because of species extinctions or introduction of non-indigenous species. This view could have significant impacts when managers have to make decisions on what their aims would be for rehabilitation.

The longer topsoil is stockpiled, the fewer viable propagules remain (Hargis & Redente, 1984). This makes fresh-stripped topsoil an extremely valuable commodity. Plant communities that develop from topsoiling will vary depending on the number of propagules in the soil and the regional climate. In arid regions, topsoiling without the supplementation of the propagule supply may increase diversity of early successional communities, but plant cover may not be high enough to satisfy reclamation regulations (Howard & Samuel, 1979). Few studies are available where long-term succession on topsoiled sites is compared to sites not receiving topsoil treatment (Luken, 1990). Revegetation is a form of managed primary succession (Luken, 1990) except that one attempts to speed up the process by a few centuries by introducing late successional species. When no attempt is made to revegetate severely disturbed soils, succession will still occur. The types of plant communities that eventually dominate such sites are controlled by chemical and physical characteristics of the disturbed soil as well as by the availability of propagules from surrounding undisturbed plant communities. The rate and trajectory of succession can be manipulated in all plant communities. There is a void that exists between ecologists and resource managers that hinders the development and general acceptance of succession management.

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Succession will continue to function as a repair process following human disturbance just as it has done since the beginnings of human transformation of ecosystems. In many situations this may be adequate resource management. In the majority of situations, however, we need to refine and augment this repair process to better preserve and use our dwindling natural resources (Luken, 1990).

At this study site, management decided to rely on natural recolonisation and succession to return plant diversity to mined areas. In this case a rehabilitated area is defined as one in which overburden was replaced after strip-mining and followed by topsoil. The area was levelled and left for natural succession to take place on its own, or tilled and then left to recover with or without the addition of Australian saltbushes *Atriplex semibaccata* (sown) or *Atriplex nummularia* (planted). Species can become established on rehabilitated areas from propagules stored in the topsoil and seed from surrounding areas transported by a variety of vectors. The seed would also be able to disperse freely to the mined area if surrounded by unmined areas. Species with poor dispersal ability might be able to invade the edges of the disturbed areas where the unmined areas are very close to the mined areas. Factors negatively influencing natural succession are the low and unpredictable rainfall, which results in low basal cover of vegetation and unprotected soil surfaces subjected to erosion by wind. Wind-blown sand damages plants and unprotected soil surfaces are subjected to high wind speeds and high temperatures, both of which promote rapid evaporation from the soil surface, drawing salt to the surface. Limited rainfall, in combination with accelerated erosion, wind scour and salinization, results in further reduction in vegetation cover.

The aim of this study was to document post-mining vegetation composition, to compare this with undisturbed vegetation, and to develop an understanding of the influence of local conditions and time on vegetation structure and diversity. On the basis of succession theory I hypothesised that indigenous plant species richness would increase with time after disturbance, that early successional communities would be dominated by ephemerals and by plant species effectively dispersed in time and space. On the basis of succession theory, I expected to find that the contribution of perennial plants to species richness and to vegetation cover would increase with time after mining disturbance.

Materials and methods

Site description

The research was undertaken at a gypsum strip-mine, 5km north of Vanrhynsdorp (31^0 33.6" S and 18^0 45.2" E) in the Western Cape Province of South Africa. The vegetation of the study area is classified by Acocks (1975) as Veld Type 31, Succulent Karoo and by Low & Rebelo (1998) as Lowland Succulent Karoo. It is a low shrubland, dominated by members of the

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Mesembryanthemaceae, especially species of *Ruschia, Drosanthemum, Malephora* and *Delosperma*. Annuals and geophytes may appear abundantly after good rain but perennial grasses are scarce.

The soils of the area consist of an orthic A horizon, therefore a lack of an organic, humic, vertic or melanic topsoil and described as Red apedal or neocutanic. A cemented sediment layer (proto-silcrete) of laterite known as duripan or dorbank follows, which in turn is followed by a gypsic horizon (Soil Classification Working Group, 1991). Mining mixes fractured rocky deposits with topsoil so that after mining the soil is rockier, with less topsoil present. The difficulty with spreading the topsoil evenly across the mined area results in the vegetation growing back patchily, with large areas of bare, hard, rocky soil.

The region is characterised by extreme summer aridity with a mean annual precipitation of 145.5mm (Desmet & Cowling, 1999), ranging from 50 to 200mm in the cool season (May to August). The average annual maximum air temperature is 23.4 ^{0}C and the average annual minimum temperature is 8.7^{0}C. The hottest and coldest months are February and July respectively, and average evaporation is 7.875mm/month.

Survey methodology

Two areas of undisturbed vegetation, and seven previously mined sites were selected for sampling. Post mining recovery periods were 16 years (4 sites), 8 years (one site), 4 years (one site) and 1 year (one site). The four 16-year old areas, had received different post-mining treatments. Two areas where grazing livestock (mainly sheep) were excluded, had been tilled and planted with wheat, one area had been planted with *Atriplex nummularia* and the remaining area had been seeded with *Atriplex semibaccata*. It is important to mention at this stage that due to the mining operations the grazing of livestock was minimal in these areas. The farmer generally kept his sheep away from the mining activities and if they did move into the mining areas they generally utilized the undisturbed vegetation. The condition of the vegetation on the different aged rehabilitated areas was described by means of three variables: years since backfilling and levelling, plant species richness per unit area and projected canopy cover. The Braun-Blanquet classes (Mueller-Dombois & Ellenberg, 1974) used in phytosociology was used to allocate values to plant richness and cover. Slightly modified Braun-Blanquet cover classes were used: r = 1 or 2 individuals, + = <1%, 2m = many but <1%, 1 = 1-5%, 2a = 6-12%, 2b = 13 - 25%, 3 = 25-50%, 4 = 50-75%, 5 > 75% projected canopy cover. Each randomly selected sampling plot was 5m x 5m in size and five relevés were taken in each of the nine treatment areas selected, which resulted in 45 relevés. The spacing between plots was at least 50m. Plant species were identified to genus level and where possible to species level. They were also classified according to the longevity of aboveground structures: Ephemerals (E), Pauciennials (P), Perennials (Per), and the presence and

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position of storage organs: Geophytes (G), Succulents (S) and Non-succulents. Table 1 contains the definitions used for these categories. The percentage cover of the biological crust were also recorded, in order to establish if it returns after mining and if its presence facilitates the return of other plant species.

Category	Definition
Ephemeral (E)	Plant species that germinate from a persistent seed bank in response to rain, flower and die within 6 months.
Pauciennial (P)	Plant species that have living aboveground structures for more than one year but less than a decade and regenerate from seed.
Perennial (Per)	Plant species that have living aboveground structures with lifespans of more than two growing seasons (Leistner, 2000) and which in the context of my research can be expected to live for more than a decade.
Geophyte (G)	Plant species that have fleshy, thickened underground parts (Smith *et al.*, 1998). Aboveground structures may be ephemeral, pauciennial or perennial.
Succulent (S)	Plant species that accumulate water in fleshy, water-storing stems, leaves or roots (Leistner, 2000).
Non-succulent (NS)	Plant species that lack storage organs, and are generally drought-deciduous in this region.

Table 3.1: Definitions used to classify plant species identified.

Statistical analysis

The extent to which recovery has taken place can presumably be determined by comparing the condition of vegetation on the rehabilitated areas with the condition of the vegetation on the undisturbed areas. Species cover data and age since rehabilitation and treatment of the different sites were ordinated using Canonical Correspondence Analysis (CCA). The ordination was done with a multivariate statistical package (MSVP v.3.12d, 1985-2001, Kovach Computing Services) and scores were detrended. After testing for normal distributions with Kolmogorov-Smirnov (Lilliefors option), analysis of variance was used to compare the percentage cover values, species diversity and species richness of the undisturbed and different mined sites with each other (Statistica version 5.5, 1984-2000, StaSoft Inc.). The species diversity was calculated by using the Shannon-Wiener diversity index (Henderson & Seaby, 2001). I created a phytosociological table (Table 3.2) by manually sorting the different relevés and species according to their cover classes,

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from high to low. Companion species, which occur consistently in low numbers in most of the relevés were also identified and listed at the bottom of the table.

Results

Canonical Correspondence Analysis

The aim of this analysis was identify trends in plant assemblages with post-mining recovery time, with treatments and with environmental variables. This will enable us to assess the relative importance of the environmental variables. The environmental gradients and the relative importance and inter correlation of the environmental variables is shown by the arrows in Figure 3.1. The length of an arrow is proportional to its importance and the angles between the arrows reflect the inter correlations between the variables. The angle between an arrow and each axis is a representation of its degree of correlation with the axis (Ter Braak, 1987). On Axis 1 disturbance was the most important variable determining the variation in species composition. On the second axis, time since disturbance and post-disturbance treatment influenced composition. Planting of *A. nummularia* had a greater effect on community composition than successional time or other treatments. Two different associations (disturbed and undisturbed) emerge clearly in separate parts of the diagram. These are species only associated with the undisturbed vegetation and not occurring in the mined areas (Figure 3.1, graphical results). The Eigen value for Axis 1 is 0.542 and that for Axis 2 is 0.265.

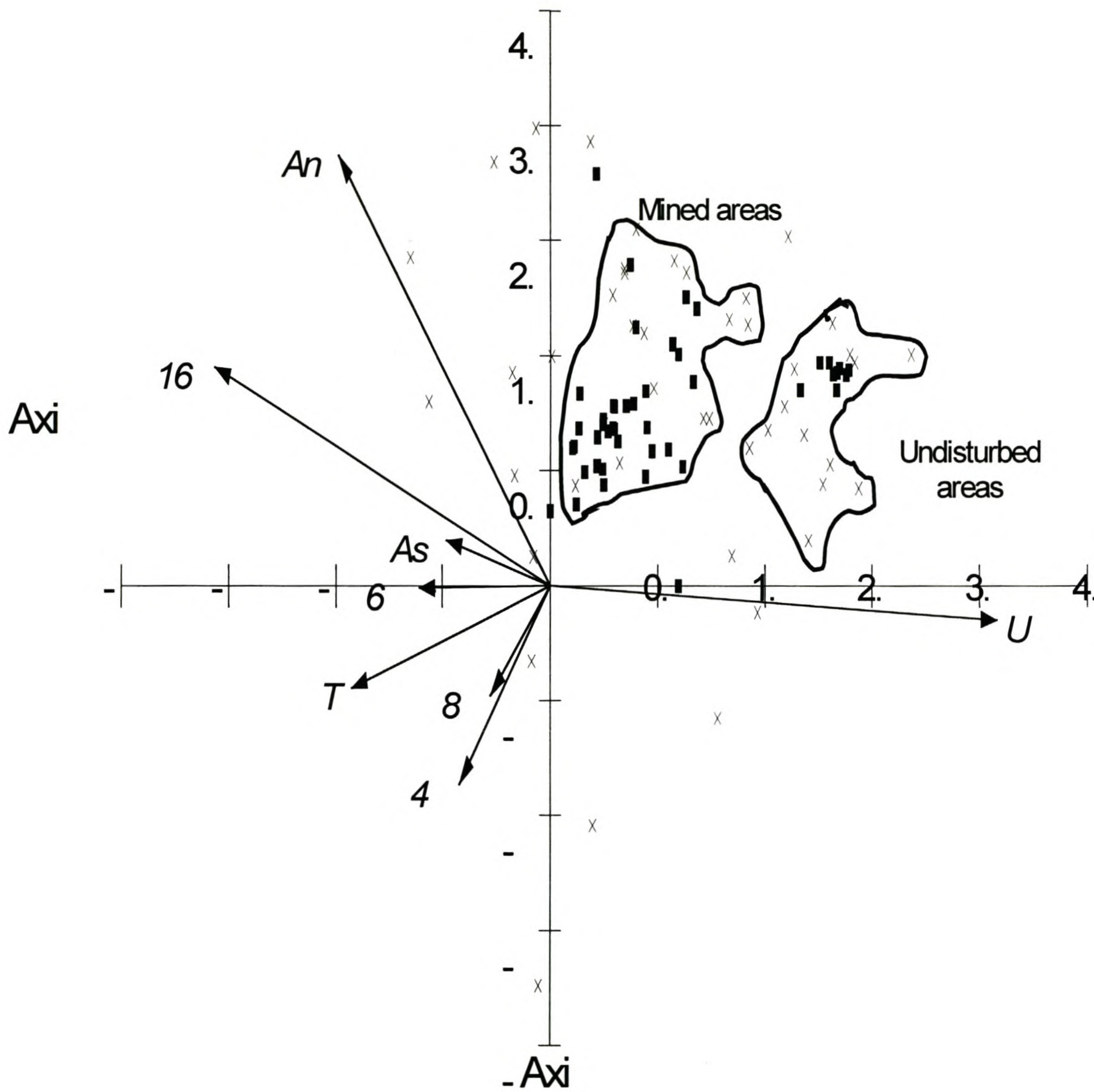

Figure 3.1: Plot of 1st and 2nd canonical correspondence axes from a detrended canonical correspondence analysis (CANOCO) ordination of species abundances, comparing plots in terms of possible effects of time since disturbance (6 = 6 mth, 4 = 4yrs, 8 = 8yrs, 16 = 16yrs and U = undisturbed >100 years), and treatment of 16 year old sites (*An* = *A. nummularia, As* = *A. semibaccata, T* = tilled). Plots could only be separated on the basis of being undisturbed or mined. Species are indicated by × and plots are indicated by ■ .

Field_code	10	9	8	6	7	43	42	44	45	21	14	15	35	34	20	19	33	2	3	4	12	23	25	26
Age	100	100	100	100	100	100	100	100	100	16t	4	4	16s	16s	8	8	16s	6m	6m	6m	4	16t	16t	16t
Total cover (%)	50	72	50	70	34	78	65	44	66	99	56	56	33	37	35	40	43	18	21	19	17	29	25	23
Differential species	**Undisturbed plots**									**Disturbed plots without *A. nummularia***														
Biological crust	3	3	3	5	3	4	3	4	3			2a	1	1	2b	+	1							
Drosanthemum species 1 (Per,S)	2a	2b	2a	2b	1	3	2b	2a	2b															
Galenia sarcophylla (E S)	1	2a	1		r	2a	1	+	2b			2a										+		
Asparagus capensis (Per,G)	r	+	1			+	+																	
Delosperma crassum (P,G)	1		2a	+																				
Aridaria noctiflora s noctiflora (Per, S)	1	2a		1													+							r
Salsola species (Per, NS)	1	+		+	1			2a						r			2a		r			+		
Galenia fruticosa (Per, N)				2a																				
Eriospermum species (P,G)			r	2a	r						+													
Cyanella orchidiformis (E,G)	r			r	+				r															
Manulea cheiranthus (E, N)				+		r	r	r																
Trachyandra species (E,G)				r	r																			
Freesia viridis (E,G)		r			r																			
Lapeirousia piramidalis (E,G)	r							+																
Diascia rudolphii (E,N)						+			+															
Helichrysum leontonyx (E,N)						+		+																
Plantago cafra (P,N)	+	r		+	r		+																	
Gorteria diffusa s diffusa (E,N)	1	1	+	+	+	+	+	1	+	+					+	+						+		+
Drosanthemum hispidum (P, S)	1	1	+	+	1		+									r	+	r				+		
Arctotis species (E,n)						+	1		1															
Drosanthemum species2 (Per, S)	+			1	+																		+	r
Leysera tenella (E, NS)	2m							+								+								
Oxalis species (E,G)	+	r	+	2m	2m	r	+	+		r		r				r								
Salsola tuberculata (Per,S)			1																					
Atriplex lindleyi s inflata (P, NS)										+	r	1					+	+	+	+	r	+	+	+
Atriplex semibaccata (P, NS)				r		+	2a		+	4	3	2b	2b	2b	2b	2a	2a	2a	2a	2a	2a	2a	2a	2a
Nemesia species (E, NS)							r								r									
Mesembryanthemum nodiflorum (E, S)															r									
Foveolina species (E, NS)																			r	r				
Erodium moschatum (E,N)										r												r		
Bromus pectinatus (E,N)							r			2m	1	r	+	2m								+	+	+
Caulipsolon rapaceum (E,G)	+	+								2b				r	+	1	r					+	+	
Atriplex nummularia (Per, NS)														1										
Oncosiphon suffruticosum (E,N)																			r					
Companion species																								
Aristida species (E,N)		1	+	1	+	+	+	+	+			+	r	r	r	+	r			r	+			
Tripteris microcarpa s microcarpa (E, N:	+	+	+	1	+	+	+	+	+	r	+		+	+	+	+	+					+		r
Amellus microglossus (E, NS)		+	+		+	+	+	+	+		+	1	+	+	2m		+					r	+	+
Foveolina albida (EN)			2m	+	2m	+	+	+		+	+			+	+	+	1	1	r	r	r		+	+
Lotononis falcata (E,N)	+	2m	2m	+	2m	+	+	+	+	+	r	+	+	+		+			r	r		+	+	
Mesembryanthemum guerichianum (E, S)			+		+	+	1		+	r	+	1	+	+	+	1	+		r	r	r	+	+	r
Senecio arenarius (E,N)		+		+		+	+		+	+	r	r		+	+	+	+		r	r	+	+	+	+
Karroochloa schismoides (EN)	+	+	+		2m		+			+		r	+	+	+	+	1	r	r	r	+	+	+	+
Tetragonia echinata (Per, S)	r	r	+	r	+	+	+		+	+	+	1	+		+	1	+		r	+		+	+	r
Osteospermum pinnatum (E, NS)	1	1	2m	2m	1	2a	1	1	2a	+	+	+	+	+	+	1	+	r			r	+	+	+
Oxalis obtusa (E, G)	+	+	+	+	+	+	+	+	+	+	r	r	r			+						r	+	
Psilocaulon dinteri (P, S)			1		+	+		+			+	1	+			r	+		r	r	+	+	r	+
Salsola kali (E, S)							r			+	+	r						r					+	
Heliophila species (E, NS)	+	r	r	+	r	+	+	+	+			r	+	r			+							
Albuca species (E, G)		r	r		r	r	r	+	r				r	r			r							
Medicago lacinata (E, NS)		r						r					r			r	r						+	
Geophyte							r	+				r					r							
Lepidium desertorum (E, NS)	r					+	+	r		r						r			+					
Ursinia nana (E N)		r		r			+							r			r					r		
Cyphia crenata (E, G)	+	+									r	r				r								
Lachenalia species (E, G)			r																					

Field_code	13	11	1	32	5	16	18	22	28	31	24	17	27	29	30	36	37	38	39	40	41
Age	4	4	6m	16s	6m	8	8	16t	16t	16s	16t	8	16t	16t	16t	16n	16n	16n	16n	16n	0
Total cover (%)	17	18	15	55	13	14	10	20	12	27	15	8	3	12	7	24	22	72	15	23	31
Differential species	**Disturbed plots without *A. nummularia*** (cont.)															**Disturbed plots with *A. nummularia***					
Biological crust				1												1	+	r		1	
Drosanthemum species 1 (Per,S)																					
Galenia sarcophylla (E S)								r		1						+					
Asparagus capensis (Per,G)																					
Delosperma crassum (P,G)																					
Aridaria noctiflora s noctiflora (Per, S)								+													
Salsola species (Per, NS)				2a																	
Galenia fruticosa (Per, N)																					
Eriospermum species (P,G)	r																				
Cyanella orchidiformis (E,G)																					
Manulea cheiranthus (E, N)																					
Trachyandra species (E,G)																					
Freesia viridis (E,G)																					
Lapeirousia piramidalis (E,G)																					+
Diascia rudolphii (E,N)																					
Helichrysum leontonyx (E,N)																					
Plantago cafra (P,N)																					
Gorteria diffusa s diffusa (E,N)											+										
Drosanthemum hispidum (P, S)																	r		r	+	+
Arctotis species (E,n)																					1
Drosanthemum species2 (Per, S)																					
Leysera tenella (E, NS)																					
Oxalis species (E,G)																					+
Salsola tuberculata (Per,S)																					
Atriplex lindleyi s inflata (P, NS)		r	r	+	+	+		+	+	+	+			+	r	+		r	r	+	+
Atriplex semibaccata (P, NS)	2a	2a	1	1	1	1	1	1	1	1	1	+	+	+	+	1	+	r	+	+	+
Nemesia species (E, NS)																					
Mesembryanthemum nodiflorum (E, S)					r		r														
Foveolina species (E, NS)																					
Erodium moschatum (E,N)																					
Bromus pectinatus (E,N)	r					r		+	+	r	1			r		+		+	+	+	+
Caulipsolon rapaceum (E,G)				+			+	+													
Atriplex nummularia (Per, NS)																+	2a	4	1	2a	2a
Oncosiphon suffruticosum (E,N)																2m	2m				
Companion species																					
Aristida species (E,N)	r	r	r		r	+	r	r	r	+							+		+	+	+
Tripteris microcarpa s microcarpa (E, N:								+		+						+	+				
Amellus microglossus (E, NS)	r	r		+	r	+		+	+	+	+	r		+	r	1	+	+		+	
Foveolina albida (EN)			r	2b	+	+	+		+	1		+		+		+	+	r	+	+	+
Lotononis falcata (E,N)			+	+	r			+		+						+			r	r	r
Mesembryanthemum guerichianum (E, S)	2m	r	+	+	r		+	r	+	r	r	+	r	+	+	+	2m	+	+		+
Senecio arenarius (E,N)				+	r	+		r	+	+	+	r		r	r	+	+	+	r	+	+
Karroochloa schismoides (EN)	+	+	r	2a	r	+	+	+	+	1	+	+			+	+	r				
Tetragonia echinata (Per, S)	r			+		r		+		+	+		r			+	+	r	+	+	+
Osteospermum pinnatum (E, NS)		r		+	r	r			r	+	+			r					+	+	+
Oxalis obtusa (E, G)		r	r	r				+				r		r				r	r		+
Psilocaulon dinteri (P, S)		2m		1			r	+		1				+		1	+			+	+
Salsola kali (E, S)	r	r				r		r		+	r	r		r		+				r	+
Heliophila species (E, NS)				+											r						
Albuca species (E, G)																					r
Medicago lacinata (E, NS)								+								r				+	
Geophyte			r	r						r							r				
Lepidium desertorum (E, NS)																					
Ursinia nana (E N)																					
Cyphia crenata (E, G)																					
Lachenalia species (E, G)																					r

Table 3.2: Braun-Blanquet cover values are displayed for all species. The following codes were used to describe the age since a quadrant was rehabilitated. 100 = Undisturbed, 6m = 6 months old, 4 = 4 years old, 8 = 8 years old, 16t = 16 years old and tilled, 16s = 16 years old and *A. semibaccata sown*, 16n = 16 years old and *A. nummularia* planted.

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The following species were considered as occasional or rare species. The plots quadrants in which they occurred are in brackets behind the name.

Ornithogalum species (6); *Hermannia concinnifolia* (6); *Romulea* species (1); *Galenia africana* (1); *Amaryllis* species (23); *Amellus* species (9); *Anthericum* species (42); *Arctotis hirsuta* (10); *Asclepias* species (10); *Bromus* species (20); *Cotula* species (44); *Crassula* species (10) *Cyanella* species (19); *Dovyalis caffra* (41); *Ehrharta delicatula* (20); *Erodium cicutarium* (23); *Gazania tenuifolia* (32); *Gladiolus* species (8); *Homeria* species (19); *Lapeirousia pyramidalis* (8); *Moraea* species (9); *Polycarena alpina* (2); *Tetragonia fruticosa* (9); *Ursinia* species (19).

Species associations

The community composition differed between the mined areas and the undisturbed areas. *Atriplex lindleyi* subspecies *inflata* and *Atriplex semibaccata* dominated some parts of the mined area and was uncommon in other parts. In most of the mined areas the presence of a biological crust was very low. Nine out of the ten undisturbed quadrants had high biological crust cover values. These areas were also dominated by *Drosanthemum* species 1, which was associated with other perennial species. Twenty-one common companion species could be identified, which occurred throughout the mined and undisturbed areas with relatively consistent cover values (Table 3.2). Almost no indigenous perennial species occurred in quadrants dominated by *A. nummularia*. Only one perennial species was found in the quadrants in which *A. semibaccata* dominated. The other 16 year old sites had four perennial species each (Table 3.2). The number of ephemeral species relative to the other mined areas were also less in the 16 year old *A. semibaccata* quadrants. High cover values of *A. semibaccata* were associated with recent disturbance, with tilled plots and with areas where this species was sown. Low cover values of A. *semibaccata* were mostly associated with the older aged quadrants or the *A. nummularia* planted quadrants. See Table 3.2 for the cover values, quadrant description and associated species. *Drosanthemum species 1* dominated the plant association on unmined areas, whereas *A. semibaccata* was characteristic of associations found on mine spoil. The degree of fidelity that these two species showed to the undisturbed and mined areas respectively could be classified as Fidelity 4 or selective species. Selective species are defined as those found most frequently in a certain community but also rarely in other communities (Braun-Blanquet, 1951). These species are therefore useful indicators of disturbance history in lowland sites near Vanrhynsdorp.

Species richness and life history

The total number of species on the mined sites where much less than the total number on the undisturbed sites. The total number of species on the 16 year old *A. nummularia* planted site is only slightly more than the 6 month and 4 year old sites. This suggests that the *A. nummularia*

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might inhibit the return of the indigenous vegetation. The number of pauciennial species does not differ between the mined sites and the undisturbed sites. The undisturbed sites however had higher numbers of ephemeral and perennial species than the mined sites.

Table 3.4 displays the total number of species in each life-history class for the different sampling sites. The averages for the two undisturbed sites and 16 year old tilled sites were taken.

Species only present in undisturbed vegetation		**Species present only in mined areas**
Non-succulent perennials	**Herbaceous plants**	**Non-succulent shrubs**
Asparagus capensis	Amellus microglossus	Galenia africana
Galenia fruticosa	Arctotis hirsuta	**Succulent shrubs**
Hermannia concinnifolia	Arctotis species	None
Salsola tuberculata	Asclepias species	**Geophytes**
Succulent perennials	Cheilanthus species	Amaryllis sp
Crassula species	Cotula species	Homera sp
Delosperma crassum	Diascia rudolphii	**Herbaceous plants**
Drosanthemum species 1	Helichrysum leontonyx	Atriplex lindleyi # A
Tetragonia fruticosa	Manulea cheiranthus	Bromus sp # E
Geophytes		Ehrharta deliculata
Anthericum species		Erodium cicutarium # E
Cyanella orch idiformis		Erodium moschatum # E
Freesia viridis		Gazania tenuifolia
Gladiolus species		Mesembryanthemum nodiflorum
Lachenalia species		Onchosiphon suffruticosum
Lapeirousia pyramidalis		Polycarena alpina
Lapeirousia species		
Moraea species		
Ornithogalum species		
Trachyandra species		

Table 3.3: Species occurring in either only mined sites or only undisturbed sites. Species marked # are non-indigenous, having been introduced from Europe (E) or Australia (A).

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Life-history class	**Ephemeral**	**Pauciennial**	**Perennial**	**Total number of species**
6 months	15	4	2	21
4 years	16	3	3	22
8 years	21	4	2	27
16 years tilled	17	4	3	24
16 years ***A. nummularia***	17	3	3	23
16 years ***A. semibaccata***	19	4	4	27
Undisturbed	37	4	6	47

Table 3.4: Total number of species in each life-history class for each sampling site. The average numbers were taken for the two undisturbed sites and the two tilled sites.

Table 3.3 shows the species present either in mined sites or undisturbed sites only. The species present in undisturbed sites are those likely to be lost during the mining process and those only occurring on the mined sites would be the early colonisers or those with a persistent soil seed bank. The number of species found on each sampling site was not related to the number of years since the site was backfilled and levelled, but a significant difference was found between the sites ($F_{6, 38}$ = 10.165, p<0.001). Significantly different means were separated using Scheffe's post-hoc test. It revealed that the undisturbed sites had a significantly greater number of species than the mined areas with p<0.01in all cases, except for the 16 year old site sown with *A. semibaccata* which did not differ significantly (Figure 3.2).

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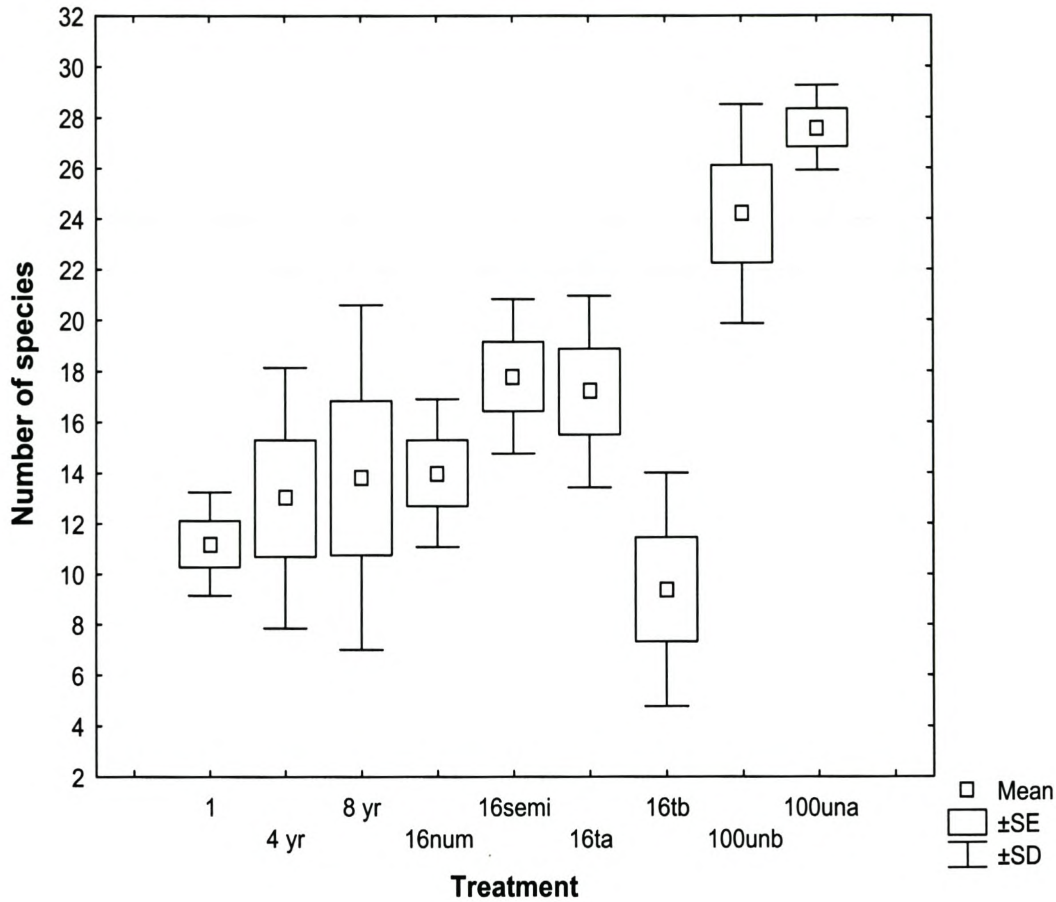

Figure 3.2: Box and Whisker plot of the mean number of species present in 5m x 5m relevès in each of the mined sites and the undisturbed areas. The abbreviations on the x-axis indicate the following: 100una, 100unb = Undisturbed, 16ta, 16tb = 16 years old and tilled, 16semi = 16 years old and *A. semibaccata* sown, 16num = 16 years old and *A. nummularia* sown, 8 yr = 8 years old, 4 yr= 4 years old, 1 = < 1 year old.

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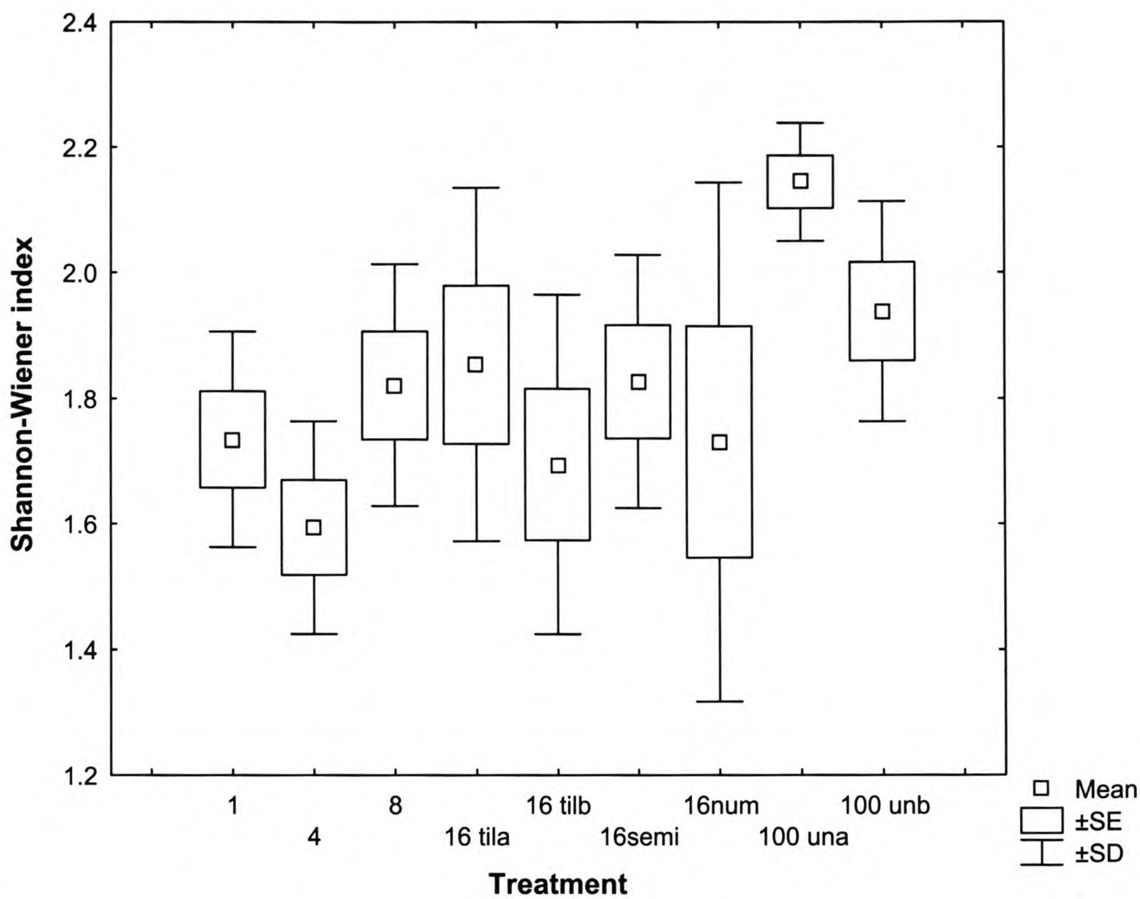

Figure 3.3: Box and Whisker plot of the Shannon-Wiener index established on the mined sites and the undisturbed areas. The abbreviations on the x-axis indicate the following: 100una, 100unb = Undisturbed, 16ta, 16tb = 16 years old and tilled, 16semi = 16 years old and *A. semibaccata* sown, 16num = 16 years old and *A. nummularia* sown, 8 = 8 years old, 4 = 4 years old, 1 = < 1 year old.

Percentage cover and species diversity

The species diversity differed significantly between sites ($F_{8, 36} = 2.285$, $p<0.05$) with the difference in means revealed by Tukey's post-hoc test as being between the lower diversity of the 4 years old site compared to the undisturbed site ($p<0.05$, Figure 3.3). A significant difference was found between the different aged sites in terms of % cover ($F_{6, 38} = 3.537$, $p<0.01$). Tukey's post-hoc test separated the significantly different means from each other. It revealed that the undisturbed vegetation had a higher percentage cover when compared to the 8 year old site, the 6 months old site and the 16 year old tilled sites with $p<0.05$ in all cases. The undisturbed sites also had a lower percentage alien cover than the mined areas (Figure 3.4).

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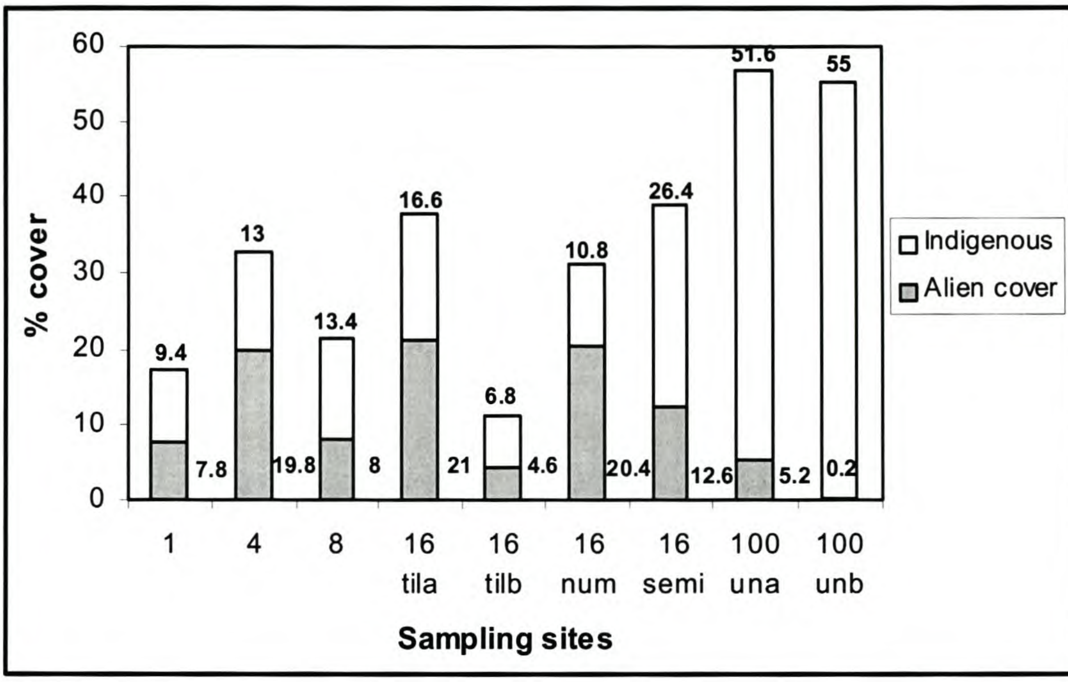

Figure 3.4: This stacked bar chart shows the total percentage alien cover and indigenous species cover for each sampling site. The abbreviations on the x-axis indicate the following: 100una, 100unb = Undisturbed, 16ta, 16tb = 16 years old and tilled, 16semi = 16 years old and *A. semibaccata* sown, 16num = 16 years old and *A. nummularia* sown, 8 = 8 years old, 4 = 4 years old, 1 = < 1 year old.

Discussion

Species associations and canonical correspondence analysis

Differences in species composition may be accounted for by soils differing among sites. Some may have received more topsoil than others or the topsoil could have been stockpiled for longer or shorter time periods before replacement. Stockpiling could negatively influence the fertility of the soil and the viable seed bank (Chapter 4). The historical effects (initial site differences) could also have influenced the successional processes on these sites and lastly, the amount of rainfall received during the year in which the topsoil was replaced could greatly influences the colonization rate of the site. This can be seen in the CCA plot where the length of the arrows (an indication of its importance) shows that the time since disturbance does not determine the abundance of species.

Fungi, algae and cyanobacteria also play an important role in reducing water loss and retaining resources in arid ecosystems. They bind surface soil particles together and form a rough

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and absorbent "living crust". This pliable crust differs from a mineral crust (or salt) in that it reduces erosion and in some cases also fixes atmospheric nitrogen (Okin *et al.,* 2001). The strong association found between the presence of a biological crust and the undisturbed areas shows that the biological crust plays an important role in retaining resources and therefore supporting high species richness, diversity and percentage cover in the undisturbed areas compared to the mined areas. The biological crust is also known to significantly alter the uptake of many bio-essential elements and increase the nitrogen content of associated seed plants (Harper & Belnap, 2001).

As expected the CCA plot has shown that the mining operations greatly influences the species composition on the different sampling sites. The post-mining treatment, planting with *Atriplex nummularia*, would definitely not be recommended due to the strong negative effect it had on the community composition.

Percentage cover and species diversity

The percentage cover values for the different mined sites do not correlate with the age since a particular site was mined, neither does the species diversity. The percentages alien cover were very variable over the mined areas, but low in the undisturbed areas. *Atriplex lindleyi ssp inflata* occurred mostly in the younger mined areas and the tilled areas, suggesting that this is a pioneer species that does not compete with the natural vegetation. The variability in the results can also be explained by the fact that different years would favour the establishment of seedlings on mined sites, which would lead to variable results due the variability of the rainfall. Therefore, when an area receives an average amount of rain the same year in which the topsoil has been respread, there is an opportunity for all plant propagules to establish themselves on that particular site. However if the topsoil respreading occurs in a drought period, the viability of the plant propagules may be reduced or lost and this particular area would be dependant on the dispersal of seeds from vegetated areas in average to high rainfall years. This results in a younger site having a higher species diversity and/or higher percentage cover than older sites. The difference between the two tilled sites in terms of species diversity and percentage cover could be due to various influencing factors, such as the variability of the soil in terms of available soil nutrients, the thickness of the topsoil and storage time.

Species richness and life history

Disturbance of arid shrublands may disturb successional processes, resulting in permanent landscape change (Okin *et al.,* 2001). Some authors argue that vegetation changes are irreversible because of the time required to reverse them (Illius & O'Connor, 1999).

In Namaqualand pioneer plants are often ephemeral species (species that germinate, grow, flower, seed and die in less than 6 months) that can only be found in the winter and spring months.

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It is therefore important to establish if, and under what conditions, pioneer species established themselves on the backfilled areas. If no germination of perennials takes place on these sites, it is likely that the environment has been disturbed too much and rehabilitation (through reseeding or translocation) would be needed. Perennials often germinate but do not survive through the summer months. In this particular case, many of the perennial species are not present in the mined areas and are likely not to return unless they are replaced artificially.

It is not obvious at this stage what the relative importance of the different species is in holding plant communities together. It is likely that some areas, particularly those covered with topsoil, will need no assistance to recover. Other areas will never recover without rehabilitation and may even degrade further. The difference in species richness between the undisturbed sites and the mined sites were expected. One would however expect that there would be differences between the different aged rehabilitated sites, but all of the 16 year old sites had more or less the same species richness and did not differ much from the 1 year, 8 year and 4 year old sites. The treatments that the 16 year old sites have undergone did therefore not facilitate the return of indigenous vegetation. The fact that very few perennial species has returned to the rehabilitated sites is possibly due to seed limitation due to the stockpiling of the topsoil. A useful study would be to test the effects of the sowing of *A. semibaccata* on the return of indigenous vegetation.

If we return to Clements' (1916) view of succession as discussed earlier, we find that nudation takes place due to mining, a fair amount of migration even takes place, but it seems when the area is left to naturally recolonize the process get stuck in the ecesis phase. This is possible due to the competition for limited resources and the unfavourable, arid conditions. Seed limitation might also play a role in this process, due to poor dispersal mechanisms and loss of the viable seedbank during topsoil storage (Chapter 4). An increase in species richness of the plant community was observed as a result of the translocation of indigenous, perennial shrubs (Schmidt, 2001, personal observation). Some rehabilitation measures should be taken to be able to move on to the reaction and stabilization phases. On the contrary, Yeaton and Esler (1990) provided evidence that the succession in the Succulent Karoo does not always proceed to a stable climax dominated by a predictable perennial plant guild. Long- and short-lived plants may replace one another cyclically on an individual basis, and composition may be determined more by plant reproductive biology and edaphic factors than by time. The successional processes taking place on a strip-mined site in the Succulent Karoo would be a combination of Clements' (1916) classical theory and the cyclical succession model which Yeaton and Esler (1990) proposed. The area, if left for natural succession to take place, is rapidly colonised, by short-lived species. It then passes into some sort of cyclical succession phase, which at this stage has not been broken. If perennial vegetation eventually establishes, I expect that the dynamics of the vegetation would pass into a more stable cyclical succession, with a mix of short-lived and perennial vegetation.

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Management recommendations

It is important to recognise rehabilitation as a gradual process that takes place at different rates in different areas. The concept that an area should be rehabilitated by a certain date may be not as useful as a program, which ensures that the process is occurring at a satisfactory rate. All possible measures should be taken to aid the recovery process and prevent further degradation. Monitoring should take place at set intervals to ensure that succession is actively progressing. Care should be taken when measures such as tilling or seeding of non-indigenous seed are employed. Methods used for rehabilitation purposes should be tested within controlled experiments before they are applied on a large scale.

Conclusions

A major conclusion from the study is that some areas can be expected to show a large degree of recovery in the space of a few years, while others would show little or no recovery over a period of decades. It is important to recognise rehabilitation as a gradual process that takes place at different rates in different areas and in different years. Tilling the soil or planting *A. nummularia* or sowing *A. semibaccata* does not facilitate the return of perennial, indigenous vegetation.

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CHAPTER 4

THE INLUENCE OF STOCKPILED TOPSOIL ON THE SOIL QUALITY AND SEEDBANK OF A STRIP-MINED AREA IN THE SUCCULENT KAROO OF SOUTH AFRICA

Abstract

The influence of topsoil removal and stockpiling due to strip-mining activities was tested by establishing the soil fertility through radish bioassays, soil laboratory analysis and the species diversity and richness of seedlings germinating from the topsoil. A higher plant species diversity and richness was found in undisturbed soil and radishes grew larger on these soils when compared to stockpiled topsoil.

Key words: bioassays, diversity, rehabilitation, richness, soil fertility, soil moisture, stockpiled topsoil.

Introduction

The Succulent Karoo, a winter rainfall desert in the western part of South Africa (Desmet & Cowling, 1999) is rich in minerals, deposited by evaporation and igneous activity. Near the Vanrhynsdorp area, a number of sites are presently being surface mined for gypsum, lime, marble, titanium, and zircon. Mining activities in this arid region are likely to increase as a result of the richness of the deposits and because mining is a major job provider in this economically undeveloped region. There is no doubt that mining is a necessary and essential component of Namaqualand's economy.

Strip-mining for gypsum in Namaqualand involves removal of the topsoil layer (to a depth of 50 mm) and destruction of vegetation. The removal of the subsoil and consequent ripping of the dorbank (duripan) that results in the exposure of the gypsum layer then follows. Topsoil and subsoil (overburben) are stockpiled in separate heaps. Stockpiles are often meters deep and soil stays in these stockpiles for time periods ranging from 3 to 12 months, depending on the situation at each site. When mining operations are complete, the overburden material is reapplied and levelled and then the topsoil is replaced and spread over the overburden, to provide a planting medium. This process involves the use of heavy equipment (Strohmayer, 1999). Motor scrapers operating on a circuit usually lift topsoil. These machines are capable of removing a very thin layer of soil so that no mineral-rich soils are lost to mining. Fairly dry conditions are needed to achieve

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this. Soils may be damaged in the process of being either removed or relocated, or are buried under tonnes of waste rock. Aggregate structure breaks down as successive layers of soil are removed and stockpiled elsewhere when mining begins (Galajda, 1999). Surface mining practices and the absence of environmental protection measures in India, have caused the destruction of land resources, i.e. denudation of vegetative cover, creation of grossly uneven topography, depletion of water resources, loss of soil and fertility, surface crusting and soil erosion. The use of surface mining techniques in South Africa has made the public and regulatory authorities very aware of such environmental impacts (Rethman *et al.,* 1999). Rehabilitation of such degraded dessert sites is a challenging task due to the harsh environmental conditions and the lack of suitable technology (Sharma & Gough, 1999).

An increased bulk density, decreased water holding capacity, chemical changes, reduced nutrient cycling, reduced microbial activity, and loss or reduction of viable plant remnants and seeds are changes that occur when soil is stored (Harley, 1976; Conners & Bainbridge, 1994; Davies *et al*, 1995; Shroeder, 1995; Lindbeck, 1999; Rethman *et al*, 1999; Strohmayer, 1999; Samaraweera *et al.,* 2000; Galajda, 1999) as in the case of the strip-mining procedure. It has also been shown that stockpiled soil that has been re-spread restricts water movement (Davies *et al*, 1995), further inhibiting air movement and bacterial growth. The surface could become as hard as a crust in summer and waterlogged in winter, during which the soil temperature will be lowered, resulting in late growth the following spring (Harley, 1976). Strohmayer (1999) has shown that the storage of soil has less adverse effects, where care is taken to minimize compaction and mixing of subsoil and topsoil. It has also been shown that the soil pH and mineral content of stockpiled soils are not affected, as long as the stockpiles are not too deep (less than 1m) or stored for long periods of time (less than 3 months). The soil microfauna recovers quite quickly once the soil is re-spread (Strohmayer, 1999). Soil, which is stockpiled more than a meter deep undergoes chemical changes, such as the accumulation of ammonia and anaerobic conditions that, occurs at the base of the pile (Davies *et al.*, 1995). Detrimental biological effects also include absence of propagules and decrease of viability of buried seeds as well as heavy losses in microbial community and decreased nutrient cycling (Ashwath *et al.,* 1999; Low *et al.,* 1999; Strohmayer, 1999). Many of the inconspicuous small soil organisms such as ants, nematodes, termites, bacteria, etc. are easily disturbed or destroyed by human activities. Their elimination can lead to undesirable changes in soil moisture relations, soil structure, fertility and plant and animal communities (Bainbridge, 2001).

The destruction of vegetation and stockpiling in dumps for several months will result in a rise of soil acidity (Harley, 1976) and loss of nitrogen (Li & Daniels, 1994; Brown *et al.*, 1999) and phosphates and it will also be lifeless and without structure (Lindbeck, 1999; Lyle, 1987). Age of topsoil is particularly important for revegetation purposes, because many of the biennial and annual plant seeds naturally present in the topsoil remain viable for only a limited time. The seed of perennial species stay viable for even a shorter time, which increases the importance of a short

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stockpiling period if at all necessary. After storage of only 4-6 months, germination could decrease greatly (Low *et al.,* 1999).

The removal of vegetation and exposure of bare soil to the weather has an adverse effect through changes in soil temperature regime. The humus of the topsoil disappears while the impacts of raindrops and of trampling by livestock are much greater on the bare soil surface (Thurrow, 1991). The result is a highly compacted concrete-like character, also referred to as sealed surface. Infiltration rates are low and surface runoff is thus high. It is very difficult for seed to lodge, germinate and establish on such a surface (Chong *et al.,* 1986).

Nutrient deficiencies may also occur in the mine over-burden material (Mcginnies & Nicholas, 1980; Davies *et al*, 1995; Rao *et al.,* 1996). Low levels of these essential plant nutrients (including nitrogen, phosphorous and potassium) will affect plant growth (Khresat *et al.,* 1998). Red colouration in the foliage of plants would be one of the deficiency signs due to a lack of phosphorus that one would be able to identify (Mikli *et al.,* 2000). Cations, particularly Na tend to leach fairly rapidly in newly formed mine soils as a result of the exposure of fresh mineral surfaces and the formation of large macropores after disturbance. After the soil settles the rate of leaching of cations decreases.

The number of seeds produced per square meter in the arid regions of southern Africa is very variable. It depends on favourable climatic conditions, levels of pre-dispersal loss and the mix of species present on the site (Milton, 1995). Seed densities in the soil in Namaqualand of the Succulent Karoo were highest (41 000 seeds per m^{-2}) in sandy, bottomlands in Goegap Nature Reserve and dominated by annual plant assemblages. It was the lowest (5 000 seeds per m^{-2}) in the same reserve on the ridge tops with scattered perennials and few annuals (Van Rooyen & Grobbelaar, 1982). Surface microtopography plays a very important role in the distribution of seeds in the soil seedbank. Larger wind-dispersed seeds are associated with adult plant cover, whereas water-dispersed seeds are found in a variety of habitats (Esler, 1999). Capsules from the tribe Dorotheanthinae in the Namaqualand area can endure for some years (Struck, 1989). At an Arizona, Sonora desert site, seed densities were highest in depressions followed by obstructions, shrubs, open areas and dry washes consecutively (Kemp, 1989).

Revegetation on the coast or northern Namaqualand near Kleinzee has shown that, of all the different methods used, covering by topsoil is by far the most effective and probably the most cost-effective treatment (Le Roux & Odendal, 1992; Fey, 1996). It contains the majority of seeds and other plant propagules, soil micro-organisms, organic matter and more labile plant nutrients (Law, 1984; Low *et al.,* 1999; Reuter, 1997) and serves as a rooting medium that should result in rapid and vigorous vegetation cover (Chong *et al.,* 1986; Le Roux & Odendal, 1992). The long-term persistent nature of soil seed banks of annuals and pauciennials in the Succulent Karoo (Van Rooyen & Grobbelaar 1982) emphasises the importance of retaining the topsoil and it is therefore very important that clearing and soil stripping should take place after seedset.

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In view of the importance of topsoil in terms of the fertility of the soil and the seed bank present in the topsoil, I will test the following hypotheses:

1. The undisturbed topsoil is more fertile than topsoil taken from stockpiles of various ages.
2. The plant species richness and diversity are higher in samples taken from undisturbed topsoil than from those taken from stockpiles.

Materials and methods

Site description

The research was undertaken at a gypsum strip-mine, 5km north of Vanrhynsdorp (31^0 33.6" S and 18^0 45.2" E) in the Western Cape Province of South Africa. The vegetation of the study area was classified by Acocks (1975) as Veld Type 31, Succulent Karoo and by Low & Rebelo (1998) as Lowland Succulent Karoo. It is a low shrubland, dominated by members of the Mesembryanthemaceae, especially species of *Ruschia, Drosanthemum, Malephora* and *Delosperma.* Annuals and geophytes may appear abundantly after good rain but perennial grasses are scarce.

The soils of the area consist of an orthic A horizon, therefore a lack of an organic, humic, vertic or melanic topsoil and described as Red apedal or neocutanic. A cemented sediment layer (proto-silcrete) of laterite known as duripan or dorbank follows, which in turn is followed by a gypsic horizon (Soil Classification Working Group, 1991). Mining mixes fractured rocky deposits with topsoil so that after mining the soil is rockier, with less topsoil present. The difficulty with spreading the topsoil evenly across the mined area results in the vegetation growing back patchily, with large areas of bare, hard, rocky soil.

The region is characterised by extreme summer aridity with a mean annual precipitation of 145.5mm (Desmet & Cowling, 1999), ranging from 50 to 200mm in the cool season (May to August). The average annual maximum air temperature is 23.4 ^{0}C and the average annual minimum temperature is 8.7^{0}C. The hottest and coldest months are February and July respectively, and average evaporation is 7.875mm/month.

Soil sampling

The six soil treatments sampled were undisturbed topsoil, topsoil stockpiled for 1 month (stockpile 1), 5 months (stockpile 5), 6 months (stockpile 6), 8 months (stockpile 8) and 1 year (stockpile 12). Treatments were not replicated. Within each treatment, 20 soil samples, consisting out of 20 subsamples of 50mm in diameter and 50mm in depth (area 19.63cm^2, volume 98.17cm^3) were taken at random. The soil samples were taken from the upper layers of the stockpile (first 50mm). The soil in each sample was well mixed and divided into three parts. One part was used for

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seedbank trials, one for laboratory soil analysis and the third for bioassays. All six soil treatments were used for the bioassays, whilst only samples of the undisturbed soil, 5 months, 8 months and 1 year stockpiled soil were used for the seedbank trials and soil lab analysis.

Seedbank trials

The seedbank densities were estimated by using a seedling emergence technique. This method provides an estimate of the viable, germinable seeds in the soil (Gross, 1990). Untested assumptions in the choice of this method were that (1) emerging seedlings were representative of viable seeds in the soil, and (2) that there was no treatment by dormancy interaction (for example, oxygen deprivation in stockpiles might affect annual dormancy more than it affects pauciennial dormancy). Twenty nursery trays per treatment were half filled with building sand. The soil samples were well mixed and a sub sample equal to the volume of six soil-cores ($589cm^3$) was taken from each of the twenty samples of each soil treatment and placed in the nursery trays. The soil in each tray was spread out evenly, to ensure that no micro topography and therefore microhabitats are created. The trays were placed in a nursery (Conservation Ecology Department of the University of Stellenbosch, Stellenbosch, South Africa) and the soil in each tray was kept moist. The trays were randomly interspersed with each other and shifted on a weekly basis to ensure that there was no effect of placement in the nursery. As the seedlings started to emerge, they were counted and identified as soon as possible. At first they were identified up to genus level, and then grown until flowering after which they were pressed and dried to be able to identify them up to species level where possible.

The effect of disturbance on a biological community is commonly measured by a change in an index of species diversity. I used the Shannon-Wiener diversity index to establish the species diversity for the seedlings germinating out of topsoil sampled from each stockpile and the undisturbed topsoil and tested the hypothesis that the species diversity would be higher in undisturbed topsoil than in stockpiled topsoil. The Shannon-Wiener index was calculated in the following way:

$H = -\sum p_i \log p_i$

where p_i is the observed relative abundance of species *i.* High diversity is associated with large values of H. A randomization procedure (related to resampling methods, involving the use of 10 000 random partitions of the data set) was used to determine the significance of the observed diversity (Solow, 1993). The total number of ephemeral, pauciennial and perennial plants were compared between undisturbed topsoil and stockpiled topsoil. The probabilities for all variables were estimated by using the Chi -square test. After testing for normality with Kolmogorov-Smirnov (Lillefors option) test, the species richness of the undisturbed soils was compared with the stockpiled soils by means of analysis of variance. Scheffé's post hoc test was employed to establish which treatments differed significantly (STATISTICA 5.5, StaSoft inc).

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Bioassays and soil laboratory analysis

Twenty, plastic sleeves per treatment were filled with the soil sampled. In each sleeve five radish seeds were planted to ensure germination. If more than one radish germinated, the others were picked out so that only one was left. The sleeves were placed in a nursery at the University of Stellenbosch, randomly interspersed and shifted on a weekly basis as to minimise any effects that placement in the nursery could have on the germination and growth. The radishes were grown for four weeks. At this stage most of them had 4-6 leaves. They were then extracted from the soil by washing the soil from the roots with water. This method ensured that most of the finer roots were salvaged. The plants (above- and below ground parts) were then oven dried for 24 hours at 70 °C and then weighed. The Munsell color guide (1952) was used to note, prior to drying, any red or yellow coloration that existed on the leaves, which indicates phosphorus or nitrogen deficiency.

The soil samples allocated for laboratory soil analysis was analysed for exchangeable cations, pH, resistance, phosphorus, nitrogen and organic carbon at BEMLA, Somerset West, South Africa. The exchangeable cations (Ca, Mg, K, and Na) were determined in a 1M ammonium acetate extract (Doll & Lucas, 1973). The amount of organic matter was established by the Walkley-Black method (Nelson & Sommers, 1982), the pH was determined in 1M KCl (McClean, 1982), resistance by a saturated paste extract and the total nitrogen was determined by digestion in a LECO FP-528 nitrogen analyser.

After testing all soil and radish parameters for normality with Kolmogorov-Smirnov (Lillefors option) test, the % C were arcsin transformed, the dry leaf mass of the radishes were squareroot transformed and the dry root mass were Box-Cox (Krebs, 1989) transformed. This was followed by an analysis of variance (STATISTICA 5.5, StaSoft inc.) to establish if the undisturbed soil is more fertile than soil from different stockpiles. The leaf- and root dry weights of the radishes were used to support the soil parameters in comparing the undisturbed topsoil with the stockpiled topsoil. I chose the 95% level of significance for all statistical tests.

Results

Seedbank

The Shannon-Wiener diversity index differed significantly among treatments. Seedling diversity was significantly greater for the undisturbed topsoil than for stockpiles 5 and 8 (Table 4.1). Seedling diversity however did not differ significantly between stockpiles 5, 8,12 and between stockpile 12 and the undisturbed soil (Table 4.1).

The undisturbed soil also differed significantly ($F_{3, 76}$ =24.326, $p<0.05$) from the stockpiled soil in terms of species richness but no significant differences were found among stockpiles of different ages. The most common species found in the topsoil sampled were short-lived

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Drosanthemum species 1, the ephemerals *Leyssera tenella, Chamaesyce inaequilatera* and a perennial *Drosanthemum* species 2 (Table 4.2). A significant difference ($\chi^2 = 63.92$, df = 2, $p<0.05$) was found between the stockpiled topsoil and the undisturbed topsoil in terms of the total amount of ephemeral, pauciennial and perennial seedlings that germinated from the soil. In the undisturbed soil, ephemeral seedlings were present in the highest numbers followed by pauciennials and perennials. In the stockpiled topsoil, however the pauciennials were present in the highest numbers, followed by the ephemerals and then perennials. When the number of species in the different life-history groups are compared, it was found that in both the stockpiled and undisturbed soil, the ephemeral species were most abundant, followed by pauciennial and then perennial species (Table 4.2). The density of seedlings that germinated from undisturbed topsoil samples was six to seven times greater than the density germinating from stockpiled topsoil (Table 4.2).

Treatment	**H**	**Variance H**	**Lower 95%**	**Upper 95%**
Undisturbed soil	2.11 ^{b}	0.0041	1.95	2.19
Stockpile 5	1.41 ^{a}	0.0426	0.89	1.65
Stockpile 8	1.58 ^{a}	0.0383	1.05	1.83
Stockpile 12	1.83 ^{ab}	0.0388	1.28	2.05

Table 4.1: The Shannon-Wiener index of species diversity (H), the variance and the upper and lower 95% confidence limits of seedlings germinating from undisturbed soil and stockpiled soil. The values with shared superscripts do not differ at $p < 0.05$.

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Species/Treatment	Life history	Undisturbed	Stockpile 5	Stockpile 8	Stockpile 12
Drosanthemum species 1	2	125	33	36	29
Leyssera tenella	1	66	2	1	1
Chamaesyce inaequilatera	1	63	2	2	0
Drosanthemum species 2	3	30	1	1	0
Psilocaulon dinteri	2	11	1	1	0
Gorteria diffusa s. diffusa	1	11	0	0	0
Gnaphalium species	1	10	1	1	0
Unidentified species		8	4	7	3
Amellus microglossus	1	7	1	1	2
Oxalis obtusa	3	7	0	0	0
Delosperma crassum	3	5	0	1	1
Lepidium desertorum	1	4	1	1	3
Karroochloa tenella	2	5	0	0	2
Galenia fruticosa	2	2	1	1	2
Malephora species	3	2	0	0	0
Aristida adscensionis	1	1	1	1	0
Mesembryanthemum guerichianum	1	1	0	2	1
Lotononis falcata	1	1	0	1	1
Conyza species	1	1	0	0	0
Dimorphotheca species	1	1	0	0	0
Gazania tenuifolia	2	1	0	0	0
Oncosiphon piluliferum	1	1	0	0	1
Foveolina albida	1	1	0	0	1
Ruschia species	3	1	0	0	0
Cynodon dactylon	1	1	0	0	2
Tragus berterionaus	1	0	2	2	0
Cotula species	1	0	0	0	2
Forsskaolea species	3	0	0	0	1
Sphalmanthus spinuliferus	3	0	0	0	3
Total seedlings (species)	--	356 (24)	50 (11)	59 (14)	53 (16)
Total ephemeral indiv. (spp.)	--	172 (16)	10 (8)	10 (10)	13 (11)
Total pauciennial indiv. (spp.)	--	140 (4)	35 (3)	38 (3)	31(2)
Total perennial indiv. (spp.)	--	45 (5)	1 (1)	2 (2)	5 (3)
Total per square meter = seedlings x (10000/(19.63x 6 cores x 20 trays) = 4.2452 m^2	--	1 511	212	251	225

Table 4.2: The species and total number of seedlings emerging in the topsoil samples taken from undisturbed and stockpiled soils. Figures in this table are totals for twenty trays per treatment equivalent of (19.63cm^2 x 6) 117.78cm^2 of soil. The different species were classified on the basis of their life history, into ephemerals (1), pauciennials (2) and perennials (3). The total number of individuals and species for each life-history classification is shown for each treatment.

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Bioassays and soil lab analysis

In order to test the hypothesis that the undisturbed topsoil is more fertile than soil sampled from various stockpiles, I compared the dry root and leaf mass of radishes grown on undisturbed topsoil and topsoil stockpiled for different time periods. The dry root mass of the radishes grown in the bioassays showed significant ($F_{5, 143}$ = 14.07, p<0.001) differences between the undisturbed soil and the soil of stockpiles 5, 8, 12. Significant differences were also found between the dry root mass of radishes from stockpile 1 and those grown on soil from stockpile 5 and between stockpile 5 when compared with stockpile 12. The dry root and leaf mass decreased rapidly from undisturbed soil to stockpile 1 and to a minimum in stockpile 5. Then it increased steeply to stockpile 6 after which it levelled off to stockpiles 5 and 8. Similar results were obtained for the dry leaf mass of the radishes as the dry root weights. Significant differences ($F_{5, 143}$ = 17.66, p<0.001) were found between the undisturbed topsoil and all of the stockpiled topsoil consecutively. A significant difference was also found between the topsoil of stockpile 1 and stockpile 5. Table 4.3 shows the mean ± SD and significant differences at the 5% level. It was also noted that a large amount of the radish leaves of those grown on stockpiled soil showed yellow coloration on their edges and red dots, which indicates nitrogen and phosphorus deficiencies.

The calcium, resistance, pH and organic carbon did differ significantly when the amounts in the undisturbed topsoil were compared with the topsoil of three other stockpiles, but there were no differences between the different stockpiles. When the undisturbed soil was excluded from the analysis of variance, some significant differences were found between the different stockpiles. The resistance values were significantly lower in stockpile 5 when compared to stockpile 8 and 12 consecutively. The organic carbon levels were significantly greater in stockpile 8 when compared to stockpile 5. Phosphorus levels were significantly greater in stockpile 8 when compared to stockpile 12. Potassium levels were found to be significantly greater in stockpile 8 when compared to stockpile 12 and lastly the SAR (sodium hazard is often expressed in terms of the sodium adsorption ratio (SAR), where the $SAR = Na/\sqrt{Mg + Ca}$) were significantly greater in stockpile 5 when compared to both stockpile 8 and 12 consecutively. See Table 4.4 for mean ± SD and probability values for stockpiled soil. The sodium and magnesium content of the undisturbed topsoil also differed significantly with the contents in the all of the three stockpiles, but stockpile 5 and 8 differed significantly from stockpile 12. The levels of both sodium and magnesium showed an increase up to stockpile 5, which was followed by a decrease to stockpile 12 and therefore closer to the pre-disturbance level. The total amount of nitrogen in the topsoil decreased from the undisturbed topsoil, followed by stockpile 5, 8 and 12 in this order. Stockpile 12 differed significantly from the undisturbed topsoil and from stockpile 5. See Table 4.4 for the mean ± SD and probability values.

Some trends could be detected in the data (shown by the lines on Figure 4.1) when the dry root mass of the radishes was plotted against the SAR, electrical conductivity, nitrogen, sodium and

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magnesium and also the SAR plotted against the electrical conductivity. The data of the dry root mass plotted against the magnesium and nitrogen shows a bell-shaped distribution. At intermediate levels of nitrogen and magnesium both high and low root mass values could be found, however root mass was limited at both high and low levels of these nutrients. The sodium levels and electrical conductivity shows a ceiling effect. The root mass decreases with increasing sodium levels. The SAR and electrical conductivity is strongly correlated (r^2 = 78%), therefore a lot of the variability in the SAR is explained by the electrical conductivity. In the U.S.A. and many other countries a level of 15 milliequivalents per litre has generally been accepted as the criterion of a sodic soil (White, 1997). The SAR is approximately equal to the exchangeable sodium percentage. As can be seen from Figure 4.1e the root growth of radishes was limited when SAR values larger the 2 occurred. The lines on Figure 4.1 were drawn to show the distribution of the data.

Treatment	**Dry root mass (g)** **Mean ± SD**	**Dry leaf mass (g)** **Mean ± SD**
Undisturbed	0.227 ± 0.196^{a}	0.181 ± 0.109^{a}
Stockpile 1	0.128 ± 0.235^{ab}	0.105 ± 0.071^{b}
Stockpile 5	0.018 ± 0.0127^{c}	0.032 ± 0.021^{c}
Stockpile 6	0.044 ± 0.033^{abc}	0.063 ± 0.030^{bc}
Stockpile 8	0.066 ± 0.074^{bc}	0.062 ± 0.042^{bc}
Stockpile 12	0.0741 ± 0.050^{b}	0.085 ± 0.040^{bc}

Table 4.3: The mean, standard deviation and results of analysis of variance and Scheffé's post-hoc test on the dry root and leaf mass of radishes, grown on undisturbed and stockpiled topsoil. Within columns, mean ± standard deviation with shared superscripts do not differ significantly at $p<0.05$.

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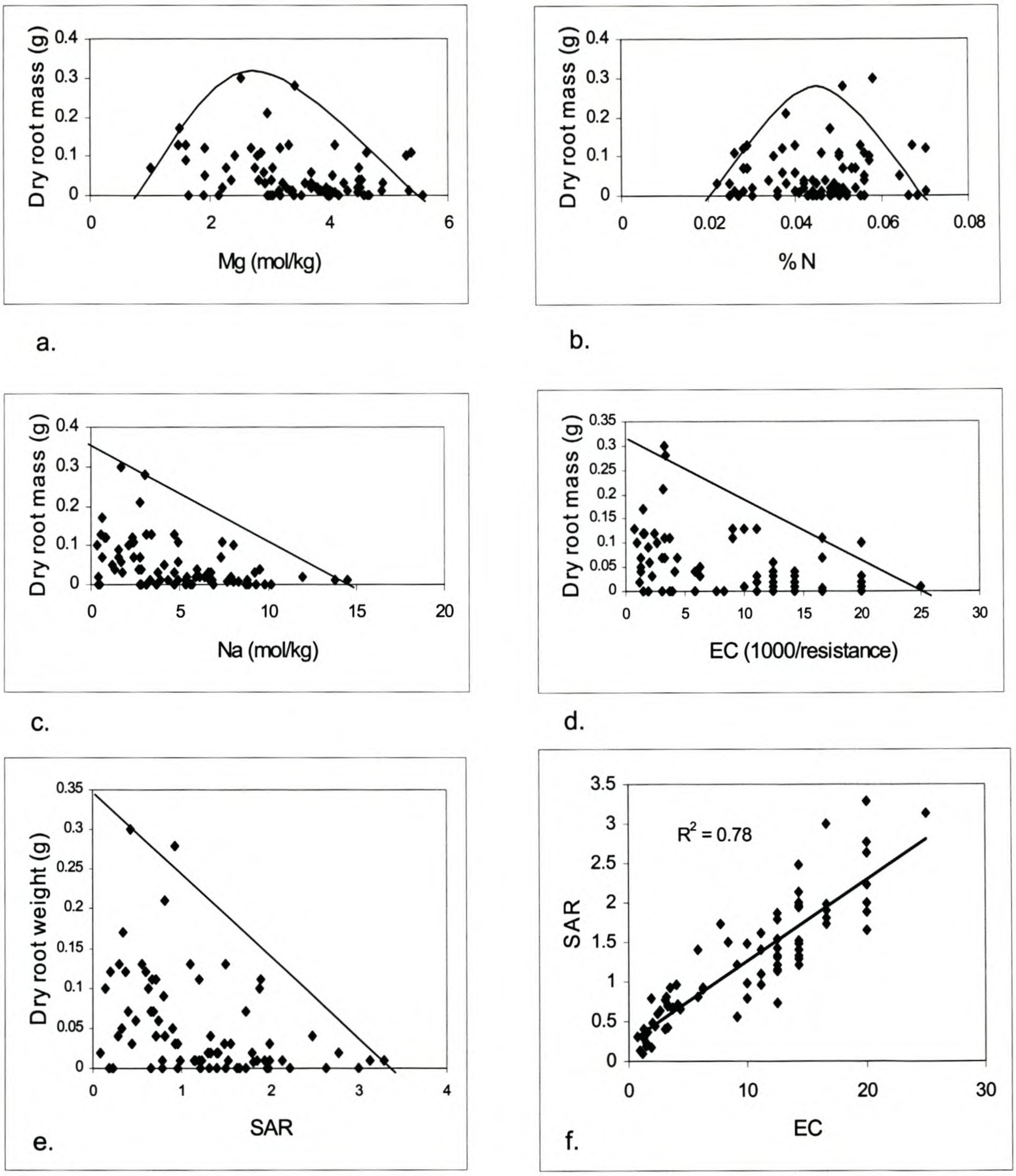

Figure 4.1: a.) Radish dry root mass plotted against magnesium concentration. b.) Radish dry root mass plotted against % nitrogen. c.) Radish dry root plotted against sodium concentration. d.) Radish dry root mass plotted against electrical conductivity. e.) SAR (sodium absorption ratio) plotted against radish dry root weight. f.) Electrical conductivity plotted against SAR.

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Soil parameters	Undisturbed	Stockpile 5	Stockpile 8	Stockpile 12	Including undisturbed		Excluding undisturbed	
					$F_{3,76}$	p-level	$F_{2,57}$	p-level
Na	1.52 ± 1.35 ^{a}	^{a} 7.69 ± 2.51 ^{bd}	^{a} 6.50 ± 2.63 ^{bd}	^{b} 3.47 ± 1.72 ^{c}	35.04	$p<0.001$	17.46	$p<0.001$
Ca	8.30 ± 6.54 ^{a}	15.24 ± 4.12 ^{b}	17.73 ± 7.25 ^{b}	14.46 ± 3.88 ^{b}	10.07	$p<0.001$	2.065	$p>0.05$
Mg	2.08 ± 0.57 ^{a}	^{a} 4.17 ± 0.47 ^{bd}	^{a} 4.17 ± 0.67 ^{bd}	^{b} 3.25 ± 0.64 ^{c}	54.98	$p<0.001$	15.53	$p<0.001$
K	1.39 ± 0.37	^{a} 1.25 ± 0.18	^{bc} 1.48 ± 0.36	^{c} 1.28 ± 0.12	2.56	$p>0.05$	4.92	$p<0.01$
P	10.0 ± 5.50	^{a} 10.10 ± 4.90	^{ab} 10.55 ± 3.99	^{ac} 7.40 ± 1.31	2.26	$p>0.05$	4.169	$p<0.05$
pH	7.25 ± 0.45 ^{a}	^{c} 7.63 ± 0.28 ^{b}	^{c} 7.68 ± 0.18 ^{b}	^{c} 7.74 ± 0.12 ^{b}	11.66	$p<0.001$	1.39	$p>0.05$
Resistance	587.50 ± 357.75 ^{a}	^{a} 77.50 ± 26.13 ^{b}	^{bc} 92.50 ± 63.81 ^{b}	^{c} 238.0 ± 134.57 ^{b}	29.8	$p<0.001$	20.62	$p<0.001$
SAR	0.69 ± 0.61^{a}	^{a} 1.91 ± 0.61^{bc}	^{bc} 1.34 ± 0.64 ^{bd}	^{c} 0.88 ± 0.37 ^{d}	17.45	$p<0.001$	15.83	$p<0.001$
C %	0.47 ± 0.16 ^{a}	^{a} 0.26 ± 0.07 ^{b}	^{b} 0.34 ± 0.09 ^{b}	^{ab} 0.31 ± 0.04 ^{b}	14.19	$p<0.001$	5.194	$p<0.01$
N%	0.05 ± 0.01 ^{a}	^{a} 0.05 ± 0.006 ^{ac}	^{bc} 0.42 ± 0.009 ^{ab}	^{c} 0.03 ± 0.009 ^{b}	10.81	$p<0.001$	14.02	$p<0.001$

Table 4.4: The mean, standard deviation and results of analysis of variance and Scheffé's test on the different soil parameters when comparisons are made between the undisturbed topsoil and the different stockpiles and also between the different stockpiles. Within rows, mean ± standard deviation with shared superscripts do not differ significantly at $p<0.05$. Superscripts before the mean show the differences excluding undisturbed soil and those after the SD shows the differences including the undisturbed topsoil.

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Discussion

Seedbank

The majority of native large-seeded herbs examined in Britain have evolved physiologies that favour rapid germination under a wide range of environmental conditions (Thompson & Grime, 1979) and therefore the main cause of death following burial is premature germination at a depth unsuitable for emergence (Schafer & Chilcote, 1970). In contrast, many species with long-lived seeds appear to have evolved mechanisms so successful in preventing premature germination that the decay rate of the seed bank in the soil is negligible over the short term (Van Baalen, 1982).

Topsoil has frequently been found to facilitate revegetation, because it has contains the seeds and provides conditions and resources conducive to plant growth (Milton, 2001). In our experiments I have shown that the disturbance of the topsoil due to mining causes a dramatic decrease in terms of species richness and diversity. The species richness and diversity of seedling assemblages that germinated under nursery conditions did not differ among topsoil stockpiles of various ages. Seeds of some plant species lose germinability more rapidly than others do when stockpiled. Perennial and pauciennial plants tend to produce fewer and shorter-lived seeds in comparison with ephemerals that produce large amounts of long-lived seed (Thompson, 1987). Later-successional species tend to produce seeds with limited longevity and dispersal abilities than early successional species (Thompson & Grime, 1979). It was also shown that later successional species had low levels of dormancy (Esler, 1993).

The topsoil in Stockpile 5 was stockpiled for 5 months, those in Stockpile 8 for 8 months and Stockpile 12 for 12 months. The sharp decrease in species richness and diversity is followed by a slight increase with time that the soil is stockpiled. The soil samples were taken only from the outer layer (50mm) of the stockpiles, which explains the initial sharp decrease in species richness and diversity of the seedlings germinating from the soil stockpiled for the shortest period. This will be followed by a slight increase in species richness and diversity as the top layer of the stockpile slowly accumulate seeds and other organic material and returns towards the pre-disturbance level. The species richness and diversity would not increase in the deeper layers of the stockpile due to the absence of light and the anaerobic conditions, which prevails. The negative effects of these conditions will be expected to increase with the time period that the soil is stockpiled and also the height of these stockpiles (Hargis & Redente, 1984). This makes fresh-stripped topsoil an extremely valuable commodity.

I support the recommendations of Le Roux & Odendal, (1992) where they advise against the stockpiling of topsoil, since it tends to smother and kill not only the seeds but also living parts of perennials that have potential to regenerate vegetatively. The best results in terms of vegetation establishment would be achieved if the topsoil were applied immediately after removal on flattened

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minespoils. In Western Australia, Tacey & Glossop (1980) has also found that the removal of the first 50mm of topsoil from an unmined area and placing it immediately on a mined area without stockpiling it, gives the best results. They have examined the seed banks of the local native vegetation to determine the feasibility of this approach (stockpiling of topsoil), and concluded that it has potential. This method will not produce vegetation identical to the local native vegetation from which they were taken, because some species may not be present in the seed banks or their seeds may lose viability rapidly when topsoil is stockpiled. However, the use of either stockpiled topsoil (short time periods) or freshly stripped topsoil can be used to establish rapidly species-rich vegetation dominated by native species that are adapted to local conditions. Low *et al.* (1999) has shown that the germination of seeds decreases greatly after 4-6 months of storage.

Seedlings germinating from undisturbed soil were mostly ephemerals followed by pauciennials with relatively few perennials. In stockpiled soil pauciennials were most abundant, followed by ephemerals and then perennials. I expected ephemerals to be most abundant in all samples. The density of seeds of various species in a seed bank is a function of the following: seed availability (as determined by the density of plants and the number of seeds produced per plant), and lifespan of the seed. An additional factor in using nursery germination trials to estimate seed banks is the dormancy of viable seeds as influenced by soil treatment prior to germination trials and also the dilution effect when soil samples are taken. The highest concentration of seeds occurs in the top 20mm of the topsoil (Bakker *et al.*, 1996). Sampling the first 50mm of soil would then result in diluting the amount of seed that could germinate in the nursery trays. The concentrations of seeds are diluted within the stockpiles as well, since deeper soil layers are often mixed with the topsoil.

The rapid decline in density of ephemerals relative to pauciennials might have to do either with the type of seed dormancy or to shorter seed life expectancies. Esler (1993) has stated that perennials at Tierberg Karoo Research Centre in the southern Succulent Karoo produces small amounts of seeds per square meter and do not persist in the soil seed bank due to seed decay, granivory or germination. The soil seed density was also not well correlated with the adult plant densities due non-uniform dispersal mechanisms of different species and the patchiness of the habitat. Many annuals that occur in Namaqualand have polymorphic seeds eg. the genus *Dimorphotheca* (Van Rooyen, 1999). Some fraction of the seeds has no dormancy, which means that the fresh seeds will all germinate within a few weeks of the soil getting wet. The other fraction of the seeds is 90% dormant. This means that only 10% will germinate when the soil is wet. Therefore in soil from undisturbed sites you can expect all the germinable fraction of the ephemeral seed bank to germinate. In stockpiled soil, the germinable fraction has already germinated. Most of the seeds that remain are either dead or dormant. For pauciennials the pattern of dormancy may be different – possibly a larger fraction of the dormant seeds becomes germinable after a few months. Another notable result from this study is that although *Atriplex* spp. (alien saltbush species

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from Australia) are abundant (see Results, Chapter 3) all over the minespoil (replaced topsoil), none was found in the in the germination trials. These plants produce great amounts of seeds. Each seed is surrounded by a spongy capsule, which easily disperses over the bare mined area by rolling over bare ground in the wind (A. Schmidt, personal observation). *Atriplex lindleyi* in particular is an aggressive transformer species, which rapidly colonises bare areas after drought (Milton *et al.,* 1997). It is still unknown if these plants facilitate or inhibit the establishment of the indigenous vegetation. The fact that they were not found in the germination trials is probably that they only establish after the topsoil is respread, since they have such good dispersal mechanisms and produces masses of seed they quickly colonise the mined area. They do not get a chance to establish in the undisturbed vegetation due the competition with the already established vegetation.

It is very difficult to explain germination data in the Succulent Karoo due to the inadequate information on germination conditions for most species. Generally, long-lived species exhibit high percentages and rates of germination, whilst short-lived and opportunistic species exhibit delayed germination and seed dormancy (Esler, 1999). The aboveground and soil seed bank can be greatly influenced by the mining procedure, since the vegetation is removed, which results that there is no more input of seed to the system. The removal of the soil and stockpiling results in a loss of the viability of the seed present in the aboveground and soil seed bank (Figure 1 in Conclusions).

Bioassays and soil laboratory analysis

Bioassays indicate that soil fertility was greatest for undisturbed soils and declined rapidly on soils stored from one to five months and then appeared to stabilise. The reasons for this pattern are that only the top layers (50mm) of the stockpiles were sampled, therefore one finds an improvement in radish growth on the soils sampled from stockpiles which were 6 months and older. The soil on these stockpiles has been subjected to a certain amount of leaching of salts (Na, Mg and Ca), which creates more favourable conditions for plant growth, since high salt concentration interfere with the osmotic processes in the roots of the plants. In addition, specific ion effects are important. Owing to its effects on both soil and plants, sodium is one of the governing specific ions.

The Na, Ca, and Mg contents of the soil have shown the opposite pattern when compared to the bioassays and seed bank trials. Here the levels increased from undisturbed soil to stockpiled soil up to a maximum from where it started to decrease again towards the pre-mining levels (Table 4.4). The concentrations of all three of these elements were much lower in the undisturbed soil possibly due to leaching from the surface layers of the soil. The total nitrogen in the soil however just decreases monotonically from the undisturbed soil over time towards the oldest stockpile of 12 months. This is possibly due to the lack of organic matter and nitrogen fixing organisms in the surface layers of the stockpiles. Visser *et al.* (1984) has found that the microbial activity, measured by respiration rates, decreases in the surface layers of stockpiled topsoil, within half a month of

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storage. Bottom layers were at higher levels, but still lower than undisturbed soil. The red and yellow coloration on the leaves of the radishes grown on the stockpiled topsoil also indicates low levels of both nitrogen and phosphorus.

Soil takes centuries to develop from parent material and organic matter. Although stockpiling negatively influences the various components of living soil as discussed above, I would agree with Rethman *et al.* (1999) and Strohmayer (1999) in that stockpiling and the subsequent reapplication of the topsoil, allows for planting conditions that are closer to the pre-disturbance condition than planting on the subsoil layers that remain. The most successful method however would be the direct application of the topsoil.

Management recommendations

A site evaluation should be completed to determine the level of compaction, rate of infiltration, organic matter, salinity, pH, texture, macronutrients, micronutrients and fungal hyphae, spores and bacteria if possible. Premining overburden analysis can be very valuable, but the influence of pedogenic processes should be kept in mind when attempting to predict the eventual chemical and physical properties of the resulting mine soil. The properties of newly constructed mine soils cannot be viewed as static (Haering *et al.,* 1993), it is also very important then to conduct post-mining soil and spoil inventories that anticipate potential rehabilitation problems (Rethman *et al.*, 1999; Sharma & Gough, 1999).

Acidifying agents for example elemental sulphur or sulphuric acid can be beneficial amendments for the more alkaline salt-degraded soils. These agents neutralize alkalinity and bring the pH into a more acceptable range for plant growth (McBride, 1994). When replacing the overburden, care should be taken to level and grade it and aim to create an area, which is self-draining. Rooting the overburden will break the hardpan of clays crushed by the motor scrapers engaged on levelling and permits the penetration of surface water (Harley, 1976).

Species representing guilds without long-term persistent soil seed banks with poor dispersal mechanisms may need to be reintroduced to the site, depending upon the extent of transformation. Species with seeds supplied in topsoil or dispersed onto the site by wind or fauna do not need to be supplied when seeding for rehabilitation purposes. Species that propagate vegetatively or reproduce quickly by seed can be supplied at lower densities (Bellairs & Gravina, 2000). When a reclaimed site lies within a relatively intact natural landscape, little or no intervention may be required beyond site preparation, if however the site is isolated dispersal agents need to be attracted to target islands in a rehabilitation site (Robinson & Handel, 2000). When rehabilitating, the species' regeneration ecology should be kept in mind if recruitment and establishment are to be maximised (Holmes & Richardson, 1999). Both dispersal in space and time (soil seed bank), of individual plant species may determine the success of management aimed at restoration of target

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vegetation. The relation between dispersal strategies in relation to habitat dynamics of certain vegetation types would be of great interest in future maintenance of restored vegetation.

Conclusions

I would like to conclude by accepting both my hypotheses, firstly that the topsoil from undisturbed areas is more fertile than stockpiled topsoil of various ages and secondly that seed bank species richness and diversity in the undisturbed soil is higher than in the stockpiled topsoil. Only topsoil that has been stored for very short periods (not longer then 1 month) should be used for rehabilitation purposes, but ideally no storage should occur and topsoil should be replaced immediately after removal onto the mined surface. This would ensure a growing medium much closer to the pre-disturbance level that could lead to fairly rapid and successful recolonization of the mined area.

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CHAPTER 5

GERMINATION, SURVIVAL AND GROWTH OF *TRIPTERIS SINUATA* AND *DIMORPHOTHECA SINUATA* SOWN IN DIFFERENT MICROSITES AFTER STRIP-MINING

Abstract

Successful plant recruitment depends on the microsites to which the seeds are dispersed. The effects of aggregation in favourable microsites may outweigh the effects of competition among these plants under some conditions. Some surface-soil microsites act as safe sites for seed germination, seedling emergence, seedling survival and plant establishment. I have found a difference between the germination of seed and the growth and survival of seedlings between different microsites. The most successful microsite for all the different stages from germination to growth and survival was shown to be the micro catchments, possibly due to the higher moisture availability within them. Moisture availability is one of the most limiting resources inhibiting the revegetation of these mined areas and therefore only years with relatively high rainfall (every 5 to 10 years) could be expected to yield good results in terms of revegetation of the strip-mined site. The higher rainfall in 2001 compared to 2000, shifted the balance between competition and facilitation from negative to positive.

Key words: competition, facilitation, microsites, rehabilitation.

Introduction

The Succulent Karoo, a winter rainfall desert in the western coast of South Africa (Desmet & Cowling, 1999) is rich in minerals deposited by evaporation and igneous activity. A number of sites in this region are presently being surface mined for gypsum, lime, marble, titanium, and zircon. Surface mining includes removal of vegetation, soils, glacial drift, shales and rock overlying the deposit, which is to be mined (Harley, 1976). Destruction of the vegetation, disturbance of the soil profile and compaction results in environmental degradation of the site. The changes in microtopography and salinity after strip-mining and the paucity of information about establishment requirements of the indigenous plants are some of the problems with successfully restoring such areas (De Villiers, 1993). These degraded landscapes are often abandoned (Barrow, 1991) because improvement requires both expensive management actions e.g. seeding and reduced income e.g. exclusion of domestic stock (Milton *et al.*, 1994). Although active management is necessary (Friedel, 1991), the economic obstacles are great.

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Successful plant recruitment depends on the microsites to which the seeds are dispersed. It has been shown from field observations that seedlings are not uniformly distributed with respect to microhabitat, which is largely the result of dispersal biology of individual species (Esler, 1993). In a variety of semi-arid environments, including the Succulent Karoo, the nurse-plant phenomenon has been described. Seedlings that occur under adult plants may experience reduced abiotic stress (Beukman, 1991). Some species are more drought tolerant and can therefore establish in the open areas, whilst others need the protection from the harsh conditions in summer (Esler, 1993). Seed limitation is also often a reason why some species cannot colonise a specific site (Ash *et al.*, 1994).

Frequency and timing of rainfall influences the relative abundance of annual species surviving to maturity. Perennial species coexist through spatial and temporal partitioning of resources and microsites. Although deep-rooted perennials out-compete colonisers of open ground, they can facilitate the establishment of shallow-rooted, shade loving succulents. Some stem succulents that need shade for establishment, become more tolerant of exposed conditions with age, outgrowing and suppressing their host plants (Milton *et al.*, 1997).

Temperature at 1mm below the soil surface may influence survival of seeds in soil seed banks. Most seeds are found on the soil surface, in cracks 0-5mm below the soil surface and soil depressions such as porcupine diggings. Higher soil temperatures and higher wind speeds mean more water stress for seedlings in the open, whilst the air humidity within a plant canopy is likely to be slightly higher than in the open because of transpiration from the canopy. These factors all contribute to a favourable microclimate under plant canopies (Eccles & Desmet, 1999). Soil fertility also builds up under canopies, creating fertile islands, which may sustain plant productivity (Danin & Gaynor, 1997, Schlesinger & Pilmanis, 1998). It is found that under shrubs the soil has a lower bulk density and penetration resistance but a greater aggregate stability. A favourable microclimate is created in terms of solar radiation, wind speed, soil temperature and evaporation rates (Bochet *et al.,* 1999). The effects of aggregation in favourable microsites may outweigh the effects of competition among these plants under some conditions.

Neighbouring adults and juveniles of the same or different species seem to have positive impacts in some instances and negative in other (Fowler, 1988). Tielborger & Kadmon (2000) have shown that the positive effects of shrubs on the understorey should dominate in dry years, while in high rainfall years, negative effects would be stronger. Negative effects are due to rainfall interception or competition for soil water, light and nutrients, whereas positive effects are related to increased nutrient availability under shrubs or to protection from heat, cold, herbivory or wind blast. The balance between these two effects would depend on the harshness of the physical environment. Some surface-soil microsites act as safe sites for seed germination, seedling emergence, seedling survival and plant establishment. If this is the case revegetation by desirable species and secondary succession will be greater (Eckert *et al.,* 1986). In the deserts of

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Uzbekistan a local microclimate between established belts of shrubs are created which ensures favourable conditions for the growth of other plant species (Reizvikh, 1999). Desert annual plants often survive in higher numbers under the canopy of shrubs. The importance of such facilitation would increase with increasing abiotic stress. Therefore, relatively dry years would result in limited growth of annuals under shrubs due to competition for water, whilst relatively favourable years would result in positive effects of shrubs on the annual understorey, due to higher nutrient contents under shrubs (Tielborger & Kadmon, 2000).

Differences in the germination of seedlings are related to seed size, shape and exposure of each microsite; physiological requirements of each species for seed germination, seedling emergence, survival and plant establishment and the effective environment present on each microsite each year (Eckert *et al.,* 1986). At the size-scale of most seeds, the soil surface on which they are dispersed is highly heterogeneous and this heterogeneity of the soil is likely to provide microsites offering widely different conditions for germination. It has been shown that microsites, located at a distance of not more than 100mm differ dramatically in their temperatures, which has significant effects on germination (Gutterman, 1997). Micro-topography exerts its effects through modifying seed-water relationships (Harper *et al.,* 1965). A suitable seedbed should provide numerous microsites for the favourable establishment of seedlings (Law, 1984).

Water harvesting is a method of exploiting available precipitation and is practised in many arid and semi-arid regions for both economic and environmental reasons (Fidelibus & Bainbridge, 1994). The use of water catchments is highly recommended for restoration projects as can be seen in trials undertaken in Arizona (150-200mm mean annual precipitation) where productivity of introduced *Cenchrus ciliaris* (buffelgras) increased fivefold over a four-year period (Slayback & Cable, 1970). A study in Kenya has shown that when pits were dug in an area and seeds liberally sown, there was no seed establishment between pits. The hard surface inhibited penetration by roots of germinating seeds. It was observed that most of the seeds were washed or blown into the pits. Regardless of the season, post-treatment plants were only able to establish in the pits (Mnene *et al.*, 1999). In the Negev desert it was found that desertification could be reversed by adding human-made pits and mounds to arid and semi-arid landscapes (Boeken & Shachak, 1994). In the Tanami Desert of central Australia, areas where topsoil was ripped into the waste rock, revegetation was generally good. Growth was especially good on furrowed banks suggesting that these surfaces were particularly conducive to seedling establishment. The rough surface provides shelter from the wind and sun for emerging seedlings and also encourages maximum water infiltration (Skousen *et al.*, 1994; Low *et al.*, 1999). Rainwater harvesting techniques used were micro-catchments, half-moon terraces, teardrop configurations and inward sloping bench terraces. Half-moon terraces, followed by micro-catchments, ridge and furrows were the most successful in experiments done on gypsum mined surfaces in North-west India (Sharma & Gough, 1999). In Cholistan (part of the Great Indian Desert), natural depressions collect water, which supports

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grasses and legumes as supplementary fodder (Ahmad, 1999). The microclimates, water harvesting, nutrient pooling from areas of runoff to areas of run-on, and suitable seedbeds are very important factors in arid regions (Bellairs & Davidson, 1999). It was observed that for fast vegetation establishment, site preparation was necessary particularly under arid conditions (Mnene *et al.*, 1999).

Whisenant *et al.* (1995) has shown with his experiments done in Texas, that concentrating water in microcatchments and re-establishing indigenous shrubs initiated autogenic successional processes leading to the development of fertile islands. Given the evidence that facilitation by established plants and micro-catchments improve vegetation establishment in arid ecosystems in other parts of the world, I hypothesised that seedling revegetation of mine spoil in Namaqualand could be hastened by provision of suitable microsites. In this article, I present tests of the following hypotheses:

1. that there is no difference in seed germination, seedling growth and survival between different microsites, and
2. that there is no difference between soil moisture in microcatchments and soil moisture on level ground.

Materials and methods

Site description

The research was undertaken at a gypsum strip-mine, 5km north of Vanrhynsdorp (31^0 33.6" S and 18^0 45.2" E) in the Western Cape Province of South Africa. The vegetation of the study area is classified by Acocks (1975) as veld type 31, Succulent Karoo and by Low & Rebelo (1998) as Lowland Succulent Karoo. It is a low shrubland, dominated by members of the Mesembryanthemaceae, especially species of *Ruschia, Drosanthemum, Malephora* and *Delosperma.* Annuals and geophytes may appear abundantly after good rain but perennial grasses are scarce.

The soils of the area consist of an orthic A horizon, therefore a lack of an organic, humic, vertic or melanic topsoil and is described as Red apedal or neocutanic. Then a platy type duripan or dorbank follows, which in turn is followed by a gypsic horizon (Soil Classification Working Group, 1991). After mining, the soil is rockier, with less topsoil present. The difficulty with spreading the topsoil evenly across the mined area results in the vegetation growing back patchily, with large areas of bare, hard, rocky soil.

The region is characterised by extreme summer aridity with a mean annual precipitation of 145.5mm (Desmet & Cowling, 1999), ranging from 50 to 200mm in the cool season (May to August). The average annual maximum air temperature is 23.4 ^{0}C and the average annual

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minimum temperature is 8.7^0C. The hottest and coldest months are February and July respectively, and average evaporation is 7.875mm/month.

Field experiments

Three plots, each 50 x 50m in size were layed out, next to each other. Each of the three plots was subdivided into a 100 smaller blocks of 5m x 5m in size. The four different experimental treatments were randomly allocated to these plots. The four treatments involved (1) the sowing of seeds in artificially created depressions in the soil of 200mm in depth and 400mm in diameter, called micro catchments (n=24 per species) and (2) on open, level areas also 400mm in diameter (n=24 per species). The other two treatments involved (3) the sowing of seeds under clumped shrubs (n=48 per species) and (4) single shrubs (n=144 per species). These were separate treatments e.g. clumps of shrubs or single shrubs were not combined with micro catchments. In each plot allocated to a specific treatment, the treatment was duplicated e.g. two micro catchments in each plot. This was done in order to eliminate any possible competition between the two different species of seeds used. The shrubs, under which the seeds were sown, were translocated from the areas designated for mining unto the post-mining surface. The translocation of shrubs will be discussed in further detail in Chapter 6.

The seeds of *Tripteris sinuata* Less. and *Dimorphotheca sinuata* Vaill.ex Moench (nomenclature follows Leistner, 2000) were used in the following seeding trials. *Tripteris sinuata* was chosen for investigating the effects of microsites on seedling germination, because it lacks a persistent seed bank, favours more sheltered microsites (Milton, 1995) and is a perennial shrub species considered to be valuable as forage for livestock and game. *Dimorphotheca sinuata* is a fast-growing winter annual that germinates readily and has potential to provide ground cover (Van Rooyen 1999). The germinability of the *T. sinuata* seeds used was 54% and that of the *D. sinuata* was 34%. These percentages were obtained by performing germinability trials on 100 randomly selected seeds of each species in the nursery at the University of Stellenbosch. Ten seeds of each species was sown in a petridish, between layers of cottonwool and kept moist. This was done with ten petridishes for each species. The number of seeds that germinated was counted in order to obtain the germinability of the seeds.

On the 24^{th} of May 2000, 130 *T. sinuata* seeds and 80 *D. sinuata* seeds were sown separately in each microsite type. The seeds were sown on the soil surface and covered with a very thin layer of soil, ± 5mm deep. The succulents used for translocation were *Aridaria noctiflora* (L.) Schwantes spp. *noctiflora, Drosanthemum deciduum* H.E.K.Hartmann Bruckmann and *Psilocaulon dinteri* (Engler) Schwantes. These translocated succulent shrubs were more or less 200mm in height and 500mm in diameter.

The seeds were only watered once, after sowing. All the newly emerged seedlings in each fixed sowing site were counted after the first rains. Later in the season (22 October 2000), survival

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and growth of seedlings were recorded. The growth was recorded by measuring the height of each seedling and the amount of leaves on each seedling. On 7 April 2001, 130 *T. sinuata* seeds were sown again at each site. The *D. sinuata* however, were not reseeded, since the germination was so low the previous season. Germination was recorded on 7 June 2001, in the same manner as described above. The seeds were not watered after seeding, since they had been sown during a rainfall event. The survival of these seeds was recorded on 27 October 2001.

Soil moisture was recorded in 2 microcatchments at depths of 50mm and 150mm. This was done with nylon probes (MCS 159) imbedded in gypsum. These probes were connected to a data logger from MC systems (MCS 120-02EX 16 channel data logger software version 3.129Y2K, 21 – 8 - 2000,Steenberg, South Africa). The amount of moisture in the soil was recorded every hour and a mean value calculated over each 24-hour period and over 12 months. The soil moisture was also recorded in open areas in a similar manner.

The soil temperature was recorded with two temperature probes (MCS 151/152). A glass probe was used to record the above ground temperature within a Stevenson screen and a plastic probe was placed 10mm beneath the soil, to measure below soil temperature. The soil temperature were recorded every hour and a mean value over each 24 hour period, over 12 months. A leaf wetness sensor (MCS 158) was also attached to the MC systems logger. This was done to establish the amount of moisture in the air, received by the plants.

The seedling leaf number was taken on each occasion as a non-destructive measure of growth. In the case of seedlings that did not survive, it was assumed that they either withered in situ when soil moisture was critically low or disappeared between sampling periods due to unknown causes. It is also important to mention that no grazing took place at the time these trials took place.

Statistical Analysis

After testing for normality with Kolmogorov-Smirnov (Lillefors option) test, the germination, seedling height and the number of leaves per seedling data were transformed using the Box-Cox transformation in order to normalise the data. This program estimates the power transformation exponent and it's 95% confidence limits to assist in choosing the best transformation to apply using the Box-Cox procedure (Krebs, 1989). The effect of treatment on the proportion of individuals emerging, the height of each individual as well as the number of leaves per individual was tested using an analysis of variance. Scheffé's post hoc test was used to establish which treatments differed significantly (STATISTICA 5.5, StaSoft inc).

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Results

Germination

Germination for both species was very low. Only 7% of the *T. sinuatum* seeds and 2.2% of *Dimorphotheca sinuata* seeds sown in 2000 germinated. In the second year (March, 2001), 9.6% of the *T. sinuata* seeds sown germinated. In 2000 the highest percentage germination was found in micro catchments (11.6%), which differed significantly from the area under a single shrub (5.76%), having the lowest percentage germination. The second largest amount of seeds germinated in open areas (9.48%), followed by the area within clumps of transplanted succulents (7.67%). In 2001 the highest percentage germination was found again in micro catchments (15.8%) that differed significantly from open areas (3.9%), which in this case had the least germination. The second highest germination was found within clumped transplants (10.7%), followed by the area under single shrubs (9.1%). It was found that the number of seeds germinating in 2001 was significantly higher when compared with those germinating in 2000 (see Table 5.3).

The seeds of *D. sinuata* germinated in the highest numbers in the open areas (7.65%) and differed significantly from the seeds germinating within clumped transplants (2.5%), in micro catchments (1.87%) and under single transplants (1.3%). See Table 5.1 and 5.2 for the mean germination, standard deviation from the mean and the results of the analysis of variance and Scheffé's post-hoc test (Box-Cox, Krebs, 1989) transformed data) on the number of seeds (*Tripteris sinuata* and *D. sinuata*) that germinated.

Seedling growth

The type of microsite in which the seeds of *T. sinuata* were sown had no significant effect on the height of the seedlings. The number of leaves formed by the seedlings in each microsite did differ significantly. Scheffé's post-hoc test has shown that a significantly greater amount of leaves were formed on seedlings in the open areas when compared with the area under single shrubs and within clumps. The seedlings in the micro catchments formed a significantly greater amount of leaves than the seedlings within clumps. The seedlings in the open areas, however still formed the most leaves. The number of leaves formed on the *D. sinuata* seedlings also differed significantly among microsites.

Scheffé's post-hoc test has shown that a significantly larger number of leaves developed on seedlings growing in micro catchments when compared to those growing under single shrubs. See Table 5.1 and 5.2 for the mean, the standard deviation from the mean, the results of the analysis of variance and Scheffé's post-hoc test Box-Cox (Krebs, 1989) transformed data on the number of leaves formed in different microsites.

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Survival

After three months, 74% (percentage of germinated seeds) of the *T. sinuata* seedlings (2000) had survived. The number of seedlings present three months after germination of those sown in 2000, a significantly greater amount of seedlings survived in the microcatchments when compared to the open areas, the area under single shrubs and within clumped transplants. A significantly greater amount of seedlings also survived in the open areas when compared with those under single shrubs. The micro catchments however still contained the highest number of surviving seedlings after three months. The number of seedlings present three months after germination of those sown in 2001 was more than the number of seeds that germinated due to the prolonged rainy season. The number of seedlings present three months after germination was significantly greater under clumped shrubs and in micro catchments when compared to open areas. The number of seedlings was highest in micro catchments, followed by clumps and single shrubs and the least in open areas. See Table 5.1. When the number of seedlings was compared between 2000 and 2001, it was found that 2001 had a significantly higher number of seedlings than 2000 (see Table 5.3). One year after germination, only 1% (percentage of germinated seeds) of the seedlings survived. The open areas were excluded in the analysis of variance, since no seedlings survived in the open. There were no significant differences in the survival of the seedlings between those in the micro catchments, under single shrubs and within clumps of shrubs due to the high standard deviation from the mean. Most of the surviving seedlings could be found in microcatchments.

Only 4% of the *D. sinuata* seedlings survived, of which a significantly greater amount survived in the open areas when compared to the area under single shrubs and within clumps. The least seedlings survived within the clumps followed by the area under single shrubs. See Table 5.2 for the mean, standard deviation and results on the analysis of variance of the survival, 3 months after germination for 2000 in different microsites.

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Treatment	**Open**	**Micro catchment**	**Single shrub**	**Clumped shrubs**	**F**	**p-level**
Germination *T. sinuata* 2000	11.8 ± 12.4 [ab]	**15.0 ± 16.6** [a]	7.5 ± 8.5 [b]	10.6 ± 11.5 [ab]	$F_{3, 237}$ =3.97	p<0.01
Germination *T. sinuata* 2001	5.0 ± 8.8 [a]	**20.5 ± 20.3** [b]	11.8 ± 13.0 [ab]	14.0 ± 14.5 [ab]	$F_{3, 237}$ =5.86	p<0.01
Nr. of leaves *T. sinuata*	**8.2 ± 3.2** [ac]	6.9 ± 2.1 [cd]	6.1 ± 2.5 [d]	5.2 ± 1.7 [b]	$F_{3, 237}$ =6.96	p<0.001
Survival 3mths of *T. sinuata* seeds sown 2000	11.5 ± 12.3 [c]	12.1 ± 11.5 [a]	4.9 ± 6.0 [b]	7.1 ± 10.3 [bc]	$F_{3, 237}$ =7.23	p<0.001
Survival 3mths of *T. sinuata* seeds sown 2001	14.4 ± 13.7 [a]	24.9 ± 13.5 [b]	19.6 ± 12.5 [ab]	24.1 ± 14.0 [b]	$F_{3,235}$ = 4.87	p<0.01
Survival 1yr of *T. sinuata* seeds sown 2000	0	0.2 ± 0.7 [a]	0.1 ± 0.7 [a]	0.1 ± 0.6 [a]	$F_{3, 237}$ = 1.311	p>0.05

Table 5.1: The mean, standard deviation and results of analysis of variance and Scheffé's test on the germination, number of leaves, the three month and one year survival of *Tripteris sinuata.* Within rows, mean ± standard deviation with shared superscripts do not differ significantly at p<0.05.

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Treatment	Open	Micro catchment	Single shrub	Clumped shrubs	F	p-level
Germination *D. sinuata*	5.8 ± 7.7 ^{a}	1.5 ± 5.89 ^{b}	1.0 ± 1.78 ^{b}	2.0 ± 4.1 ^{b}	$F_{3, 23}$=12,00	p<0.001
Nr. of leaves *D. sinuata*	6.2 ± 2.53 ^{ab}	5.13 ± 1.7 ^{b}	7.8 ± 5.3 ^{a}	7.9 ± 7.2 ^{ab}	$F_{3, 237}$ =3.25	p<0.05
Survival 3 mths of *D. sinuata* seeds sown	2.7 ± 5.1 ^{c}	1.2 ± 4.2 ^{ca}	0.4 ± 1.2 ^{ab}	0.2 ± 0.7 ^{ab}	$F_{3, 237}$ = 7.23	p<0.001

Table 5.2: The mean, standard deviation and results of analysis of variance and Scheffé's test on the germination, number of leaves and the three month survival of *D. sinuata*. Within rows, mean ± standard deviation with shared superscripts do not differ significantly at p<0.05.

Year	2000	2001	F	p-value
Germination	9.4 ± 10.9	12.5 ± 14.2	$F_{1, 478}$ = 3.98	p<0.05
Survival	6.8 ± 8.8	20.5 ± 13.3	$F_{1, 478}$ = 205.23	p<0.001

Table 5.3: The mean ± standard deviation and results of analysis of variance on the germination and survival of *T. sinuata* in 2000 compared to that of 2001.

Soil moisture

The rate of soil-moisture depletion was greater in micro catchments than in the open, level areas at a depth of 150 mm. The amplitude of the soil-moisture oscillations did not differ between micro catchments and open areas (Figure 5.2b). At a depth of 50mm there was no relationship between the rate of soil-moisture loss and microsite (Figure 5.2 a).

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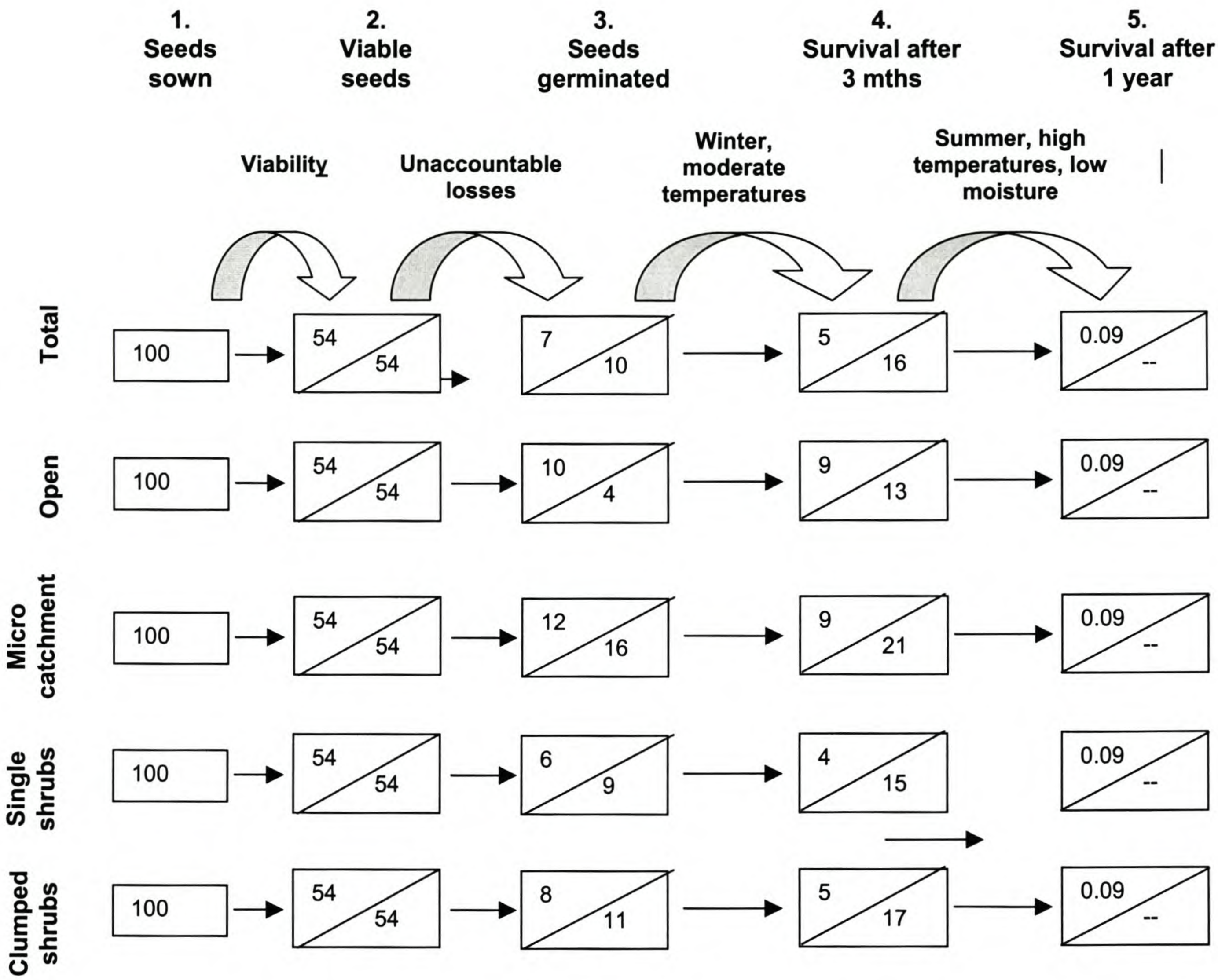

Figure 5.1: The percentage (rounded) germination and survival of seeds sown (*Tripteris sinuata*) within the different microsites is displayed in order to show where the greatest losses occur from the stage where the seed has been sown until one year after sowing. The percentages in the top part of the boxes are for 2000 and those in the bottom part for 2001. The data for the one year survival for 2001 was unobtainable due to the limited study period. The 2001 figures are greater three months after the first count (box 3), due to the prolonged rainy season, which resulted in more seeds germinating later in the season.

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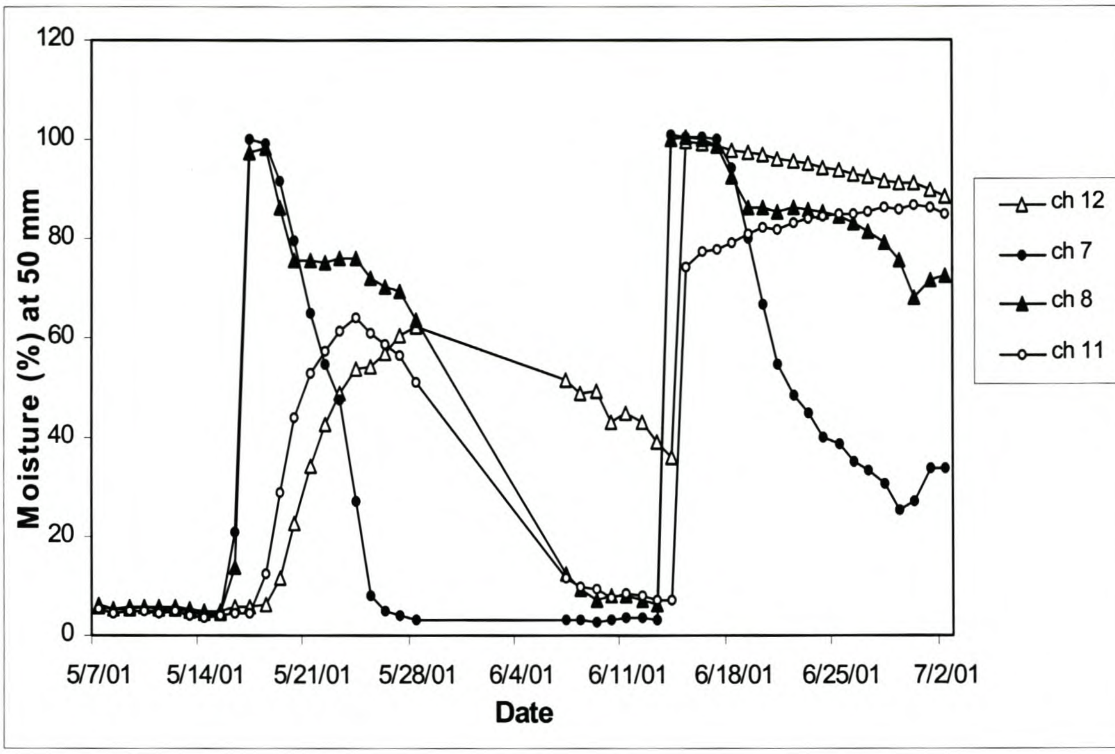
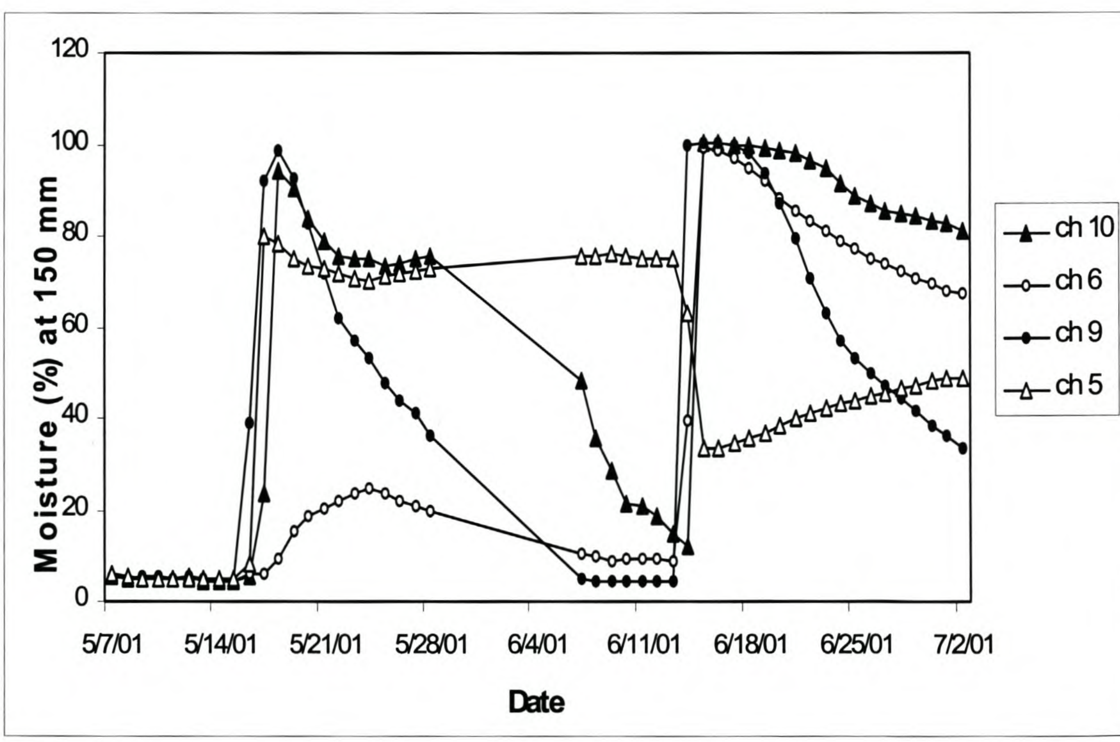


2 a.)



2 b.)

Figure 5.2: Soil-moisture fluctuations in microcatchments (● o) and in open, level areas (Δ σ) a.) 50mm and b.) 150mm below the soil surfave from 7 May to 2 July 2001. Soil moisture is expressed as a fraction of the saturated volumetric water content.

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Discussion

A favourable microclimate within a clump is created in terms of solar radiation, wind speed, soil temperature and evaporation rates (Bochet *et al.*, 1999). Dean & Milton (1991) also suggested that the best site to germinate for a seed is under a shrub and a good compromise would be to end up in an animal excavation. They also mentioned that scoops in the soil made by foraging mammals would be particularly important as germination sites in areas where the soils are hard and dry. Our results however, have shown that the microclimate created within a clump will not always be the most favourable site for germination or even growth of seedlings. The balance of facilitation and competition appears to vary with the life stages and physiologies of interacting species (Holmgren *et al.*, 1997), indirect interactions with other neighbours (Miller, 1994) and the intensity of abiotic stress experienced by the interacting species (Bertness & Callaway, 1994). However, the factors that determine the balance between positive and negative effects are poorly understood (Callaway & Walker, 1997).

Germination

During this study, dying seedlings almost always became brown and dried out without any visible damage, not disappearing until several weeks later and seedling deaths occurred primarily during periods of low soil moisture. This implies that a shortage of water was the primary cause of seedling death, since the precipitation received in 2000 was far below the long-term mean annual rainfall (78mm, 51% of the long-term mean annual rainfall). Some years may be expected to favour establishment. Since water seems to be the most limiting factor for germination in these arid areas, the water trapping function of the microcatchments helped to collect more runoff for the germination of these seeds. In the case of *T. sinuata*, seed germinated in the highest numbers in the micro catchments in both 2000 (below average rainfall year) and 2001 (above average rainfall year, 42% above the long-term mean annual rainfall). The open, level areas were the second most favoured sites to germinate in 2000, but the least favoured in 2001. Although open areas are more exposed, there is less competition for moisture with other individuals. In a below average rainfall year when moisture is the most limiting resource, the germination would be higher in the open due to the favourable moisture conditions in terms of competition. During average- or above average rainfall years when moisture availability is possibly not critically limiting, more seeds germinated under nurse plants than in open sites. In dry years, less seeds would therefore germinate under transplanted succulents. In relatively wet years when the competition for moisture is not so limiting, the shrubs would have an added positive effect of protection against sun, wind and therefore high water evaporation from the soil, resulting in even higher moisture availability. Contrary to this statement more seeds germinated under clumps of transplanted succulents than under those

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planted alone in 2000 and 2001. Although there should be more competition for moisture under the clumps than under isolated transplants, the clumps would provide much more shade and therefore lower temperatures and reduced water evaporation from the soil. The moisture availability might therefore have been higher within clumps than under succulents planted alone. In view of the above results, I could therefore support the findings of Tielborger & Kadmon (2000). They have shown that temporal environmental variation tips the balance between facilitation and interference in desert plants. Depending on the species, the effects of shrubs on annuals changed from either negative to neutral or from neutral to positive with increasing rainfall. Therefore in very dry years shrubs would compete with annuals for survival and therefore the competition would override the facilitation effect. I agree with Tielborger & Kadmon (2000) that even this facilitative effect would override the competition only in relatively good rainfall years (above or at the long-term average rainfall), but in a below average rainfall year plants will compete for moisture. Holmgren *et al.* (1997) used a graphical model to show that the condition required for facilitation to occur is that improvement in an environmental factor (e.g. moisture, nutrients, herbivory) under the canopy must exceed the increased demand for that factor caused by deterioration in another factor (e.g. light). The net effect of nurse canopies on the understorey may easily shift from facilitative to competitive, or vice versa, when conditions change.

Seedling growth

Our results could be explained in view of the fact that stress which results from abiotic factors such as low water, low nutrients or high temperatures, limits plant growth (Whisenant, 1999).

The germination rates for *D. sinuata* were the highest in the open areas, whilst the growth was highest under transplanted shrubs. This was expected, since desert annuals are usually more abundant and shows higher growth rates under shrubs than in the open, due to the favourable microclimate, which reduces stress from abiotic factors (Tielborger & Kadmon, 1995). *Tripteris sinuata*, however, showed greater germination and growth rates in open areas and micro catchments when compared to the area under shrubs. In this case, the facilitative effects that the shrubs had to offer were overridden due to the competition for moisture between the shrubs and seedlings.

Survival

After three months the number of *T. sinuata* seedlings (2000) was significantly greater in micro catchments than open areas, under clumped transplants or under the single transplants. Three months after germination the temperatures were still fairly low and therefore the conditions less harsh. The need for protection against sun and wind is much less than in summer. As summer approached with a rise in temperatures and local warm winds, the conditions became much harsher and seedlings began to whither and die. The most favourable microsite under these

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conditions were still the micro catchments, where after one year the most seedlings survived. Our results support that of Milton *et al.,* (1994) who found that seedlings died within one year of emergence, mainly because of lack of follow-up rainfall. Only 0.1% of the seedlings of all seeds sown, survived after one year in our trials, which was most likely also due to the lack of rainfall. In 2001, a greater number of seedlings were counted than during the initial germination phase (after the first rains). The prolonged rainy season and cool temperatures allowed the germination of seeds over a longer period than in 2000, which resulted in the second count actually having a larger number of seedlings. The higher rainfall of 2001 enhanced the germination and survival of seedlings. In 2001 the balance between competition and facilitation shifted from that in 2000. In 2000, the rainfall was very low and competition for resources overrode the facilitation effects that shrubs should have on the survival of seedlings, since more seedlings survived in the open (9%) and micro catchments (9%) than under single shrubs (4%) and under clumped shrubs (5%). Percentages were calculated from the number of seedlings that emerged and not the number of seeds sown. In 2001, however, the balance was shifted towards facilitation and not competition for resources. Most seedlings were found once again in micro catchments (21%), followed by seedlings under clumped shrubs (17%), seedlings under single shrubs (15%) and the least in open areas (13%). Moisture availability therefore plays an integral role in the survival of seedlings under these harsh conditions.

In view of the above results I conclude that sheltered microhabitats which can provide more moisture to the germinating seed and young seedlings, have to be created to facilitate return of some species of plants to mine spoil (Craig, 1985; Eckert *et al.,* 1986; Aguiar *et al.*, 1992; O'Connor, 1991). Our results support the findings (Schuman *et al.*, 1994; Milton, 1995; Ludwig & Tongway, 1996) that, by creating favourable moisture conditions, the biomass and cover of naturally seeded annuals and perennials will increase. When favourable microhabitats are created by managing the physical environment (Milton *et al.*, 1994), the natural seed abundance may be sufficient to recreate vegetation patches, which will act as sink areas (Ludwig & Tongway, 1995), and become fertile patches, which expand over time. The clustered resource distribution on rehabilitated arid mine sites is an improvement over the homogenous but uniformly low resource levels in mined sites with little vegetation.

It has been shown however, that the relatively small microcatchments used in these trials have a finite lifespan, determined by erosion rates. Microcatchments therefore seldom expand (Whisenant, 1999). Water-harvesting strategies such as pitting and furrowing also has generally short-term benefits (Vallentine, 1989). Whisenant *et al.* (1995) has shown that the creation of much larger (100mm deep and 1.5m^2) depressions in the soil also accumulate water, soil, nutrients, organic matter and propagules, which may be essential factors in the initiation of autogenic landscape restoration. These larger depressions have a longer lifetime and therefore a prolonged

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effect as a microcatchment. Thereafter, biological mechanisms that alter the soil, micro-environmental and -nutrient relations through vegetation, particularly shrubs, may dominate.

In summary, many aspects such as seedbed ecology, seed dormancy mechanisms and establishment requirements of native species are still unknown (Bellairs & Davidson, 1999; Redente & Keammerer, 1999; Sharma & Gough, 1999). In no plant community is the role of species-specific requirements for germination and establishment well understood and few communities have had the safe sites for some of their species characterised (Fowler, 1986). It would however be impossible to obtain all the above-mentioned requirements for every single species, therefore it is important to know which species occurred in the area before disturbance, which of these are most necessary to replace and what their establishment requirements are, in order to recreate a functioning ecosystem. Very little is known about the long-term success of native vegetation establishment on mined lands and the ability of rehabilitated vegetation to cope with future disturbances. Research therefore needs to be conducted on the decommissioning of mine-sites in arid pastoral regions and on their resilience to grazing and the impact of grazing (Bellairs & Davidson, 1999).

Callaway & Walker (1997) also address the need for long-term experiments, designed to examine the balance of competition and facilitation, while varying physical stress and age, size, and density of benefactors or beneficiaries, would contribute much to a synthesis of competition and facilitation in community ecology. In Namaqualand, South Africa, there is also a need for experimentation to decide which of the many factors is the most limiting to long-term ecosystem recovery. To enable us to restore lost productivity and maintain plant species diversity, information on these limiting factors on denuded and altered soils is needed (Milton & Dean, 1999). On these mined areas it seems that low soil moisture and high soil salinity would be the most limiting factors for vegetation establishment and growth (see Chapter 2).

Soil moisture

Although seedlings established and survived in greater numbers in micro catchments compared to the other microsite types, the soil moisture was not higher in the microcatchments and neither did they retain the water for longer when compared to the level, open areas. One would expect the micro catchments to collect more runoff water and retain the moisture for longer periods, since a micro catchment is partly shaded during the day. The disturbance of the soil, whilst creating the micro catchment, could have influenced its ability to retain the water received. Local differences in soil structure could also be the reason for the mixed results. Since the logger only allowed me to compare two open, level areas with two micro catchments, I can still not be sure if it is the higher moisture content of micro catchments which results in the higher number of seedlings establishing and surviving in micro catchments.

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Management suggestions

Figure 5.1 shows the losses that occur during the different stages, from seeding to survival of the seedlings one year after germination. All the percentages shown were calculated form the initial amount of seeds sown. A great loss occurs due to the often low seed viability and germinability. In the next phase, germination to three months survival, the losses are quite small. Great losses again occur from this stage to survival, one year after germination. I would therefore recommend that strip-mining companies should revise their management plans and not create a smooth and level surface after backfilling, but rather leave some small-scale depressions. This would create a type of microcatchment that would facilitate the germination of seeds and establishment of seedlings, possibly due to the favourable moisture conditions. It is also advised that seeding should take place over a number of years to yield positive results in terms of the financial inputs when compared to the amount of revegetation that is achieved. Due the variability in rainfall and therefore germination of seed, growth and survival of seedlings, some years almost no success would be achieved whilst other years may yield positive results. In order to increase the number of surviving seedlings, management could be done at the germination phase or the surviving phase, three months after germination, if sufficient resources are available. These management procedures could include watering at critical stages and providing some form of shade and protection against wind or herbivory.

Based on my seeding trials, it would be necessary to sow 0.189 kilograms of *Tripteris sinuata* seed to achieve a density of more or less a 1000 plants/ha in a dry year, and 0.063 kg to achieve the same density in a wet year. At a cost of R50/kg, the seed would cost a land manager R9.45/ha in a dry year and R3.15/ha in a wet year. These calculations are based on seedlings surviving eight months after germination, therefore the number of plants/ha will decrease with time due to the mortality of seedlings. I would therefore recommend that more seed should be sown to allow for seed predation, herbivory and dying of seedlings due to the harsh conditions. It would be more realistic to sow 1 kg/ha *Tripteris sinuata* in dry years and 500g/ha in wet years.

Conclusions and Recommendations

I would like to conclude by rejecting my null hypotheses. My experiments indicate that there is a difference between the germination of seed and the growth and survival of seedlings between different microsites. The most important microsite for all the different stages from germination, growth to survival was shown to be the micro catchments, possibly due to the higher moisture availability within them although I could not prove this, due to the mixed results from the logger data. Moisture availability is one of the most limiting resources inhibiting the revegetation of these mined areas and therefore only years with relatively high rainfall (every 5 to 10 years) could be

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expected to yield good results in terms of revegetation of the strip-mined site. This makes the reseeding of strip-mined areas in the Succulent Karoo a risky operation.

Therefore seeding within micro catchments as a restoration method for strip-mined sites in the Succulent Karoo has the potential to recreate vegetated areas that will further capture and conserve scarce resources and improve soil conditions.

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CHAPTER 6

EFFECTS OF CLUMPING ON SURVIVAL OF THREE SUCCULENT PLANT SPECIES TRANSLOCATED ONTO MINESPOIL

Abstract

The translocation of succulent plants has been investigated for the revegetation of gypsiferous minespoil. Given that facilitation effects are thought to outweigh competition effects in harsh environments, I hypothesized that the survival of translocated succulents would be higher when planted in clumps than alone and the growth rate (measured as stem extension) and seedset would be greater for plants in clumps than for those planted alone. Two leaf-succulent (*Aridaria noctiflora sp. noctiflora* and *Drosanthemum deciduum*) and one stem-succulent (*Psilocaulon dinteri*) were translocated from the area destined for mining onto the minespoil. These plants were panted either three together in a clump or alone. It was found that the succulents used in these experiments survived in higher numbers when planted alone. Due to the similar root morphology of *Drosanthemum deciduum* and *P. dinteri* they competed for resources instead of facilitating each other's establishment. The growth and seedset of the transplanted leaf-succulents used were not higher in clumps. The results were variable for each of the species used and clumping was not correlated with either growth or seedset. These findings could vary from year to year with different abiotic conditions.

Key words: arid, clumping, facilitation, minespoil, translocation.

Introduction

The Succulent Karoo is considered a global hotspot of biodiversity with many endemic succulent plant species (Milton *et al.*, 1997). The ecological conditions that seem to favour the dominance and diversity of succulents in the Succulent Karoo are low but predictable rainfall (Milton & Dean, 1999). There are approximately 50 endemic genera of Mesembryanthemaceae (Goldblatt, 1978) and a third of the world's 1000 species of succulents occur in this region (Van Jaarsveld, 1987). The Succulent Karoo flora includes 730 genera of which 67 are endemic (Hilton-Taylor, 1996).

There are also rich deposits of diamonds, gypsum, titanium, marble and zircon beneath the shallow soils of this region. Strip-mining used to extract these minerals destroys overlying vegetation and changes soil structure (Milton *et al.*, 1997). In terms of National Environmental Management Act (DEAT, 1999), there is a requirement that mine tailings are

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rehabilitated to a state that can support pre-mining landuse. The region is too dry to support dry-land agriculture, and, where no irrigation is available, the economy is based on extensive stock ranching and tourism. This requires that species-rich, indigenous, perennial vegetation be returned to mined sites. Saline soils, summer drought and low rainfall exacerbate the problems associated with vegetation re-establishment on denuded ground.

The strip-mining method will vary with the type of material being mined, natural conditions in which the material is located, and the type of equipment available for use (Law, 1984). The gypsum mining in Namaqualand involves the removal of the first 50mm of topsoil and the consequent destruction of the vegetation. The topsoil is placed in low heaps surrounding the quarries. The subsoil is then removed, which involves ripping the dorbank (duricrust) and placing it in heaps next to the topsoil. The underlying gypsum deposit is then exposed. After mining, the subsoil is pushed back into the quarry, followed by the topsoil. The area is then graded, levelled and left in order for natural colonisation to take place. Disturbance of the soil profile and compaction results in environmental degradation of the site.

In arid systems constraints are such that the revegetation goal is usually to restore as many aspects of natural vegetation as possible. To do this I need to know what natural vegetation in this system looks like and how it works (Eccles & Desmet, 1999). It has been found that plants in Karoo shrublands are often arranged in multispecies clumps on fertile islands (Dean & Milton, 1999). The reasons for these patterns are also most certainly related to dispersal mechanisms and differential survival of plants in protected and exposed sites. Some authors however feel that the clumped vegetation pattern is due to pseudo-interaction (Garret & Dixon, 1997). This view involves abiotic environmental heterogeneity, which could produce spatial characteristics that suggest interactions even in the absence of actual interactions (Schlesinger *et al.*, 1990, Jones *et al.*, 1997, Reynolds *et al.*, 1999). The benefits to individual plants could be that plants are protected against grazers and strong winds (Callaway & Walker, 1997; Tewksbury & Lloyd, 2001). Measures in the field in arid-land communities have shown that while some plants were regularly dispersed, many species were clumped. These clumps contain a variety of species. It is hypothesised that clumps trap fine particulate matter that includes organic matter, litter and spores of mycorrhizal fungi. This could potentially benefit the plants. Individuals of different species are more likely to form clumps than those of similar species, since their roots may not have the same placement and they can in this way avoid competition between species with the same rooting requirements. Plants growing together in a clump are thought to facilitate each other's survival. Facilitation occurs if early colonizers change the environment enough to allow new species to establish. It is also viewed as the process where two individual plants interact in such a way that at least one exerts a positive effect on the other (Vandermeer, 1989). Various studies have also shown that vegetation structure is an important driving

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variable for animal community diversity for example the branch density of different shrubs can alter the spider community composition, since different spider species utilise shrubs with different branch densities for the building of their webs (MacMahon, 1987).

Successful rehabilitation of strip-mined sites requires selection of suitable plant species (Law, 1984; Warren, 1989; Abu-Irmaileh, 1993; Van Rensburg *et al.*, 1998), modification of the soil at the planting site and in situ water harvesting techniques. It is difficult to establish any vegetation on such sites due to harsh environmental conditions in arid areas and because revegetation of mine spoils poses the problem of adaptation of plants to the unusual soil conditions (Rao & Tarafdar, 1998; Pieterse, 1999; George & Bell, 2000). Parameters such as physical components of the soil profiles and seasonal conditions appear to be critical in determining the resultant species assemblages that occur on a particular rehabilitation area (Samaraweera *et al.*, 2000).

There are many advantages of using local indigenous species for the rehabilitation of disturbed land (Rethman *et al.*, 2000). The use of these species on a mined area would result in the development of plant communities that are self-sustaining over the long-term and would result in a more diverse plant community with greater stability and a greater variety of habitats to wildlife than would exotic species. Many alien weed species are not as long-lived in arid and semi-arid environments as adapted indigenous species. Indigenous species would also be the best choice to facilitate succession and from an aesthetic point of view (Redente & Keammerer, 1999).

A stable landform and growing medium would be the initial requirements for the establishment for native vegetation (Bellairs & Davidson, 1999). Only plant species that have evolved through natural selection and become adapted to these unstable, exposed conditions and highly saline soils can colonise such sites. The seeds of many indigenous species therefore have the ability to survive on these sites, given that they are present in the soil seedbank or possibilities exist for their dispersal and establishment.

An effective way to initiate natural recruitment is to transplant some established plants onto the post-mining surface (Milton, 2001; Burke, 2001). The presence of established plants would provide appropriate microclimates for recruitment and reduce the exposure of recruits to various sources of risk. If planted in the correct arrangement and density, transplants will provide the necessary seed trapping function (Eccles & Desmet, 1999). Shrubs facilitate the development of islands of fertility, by trapping organic matter and therefore they accumulate nutrients in shrubland ecosystems (Whisenant, 1999). It is found that under shrubs the soil has a lower bulk density and penetration resistance but a greater aggregate stability. Transplanting plants could have different success rates in arid areas, depending on the rainfall for that particular year. Watering transplanted species during drought will result in green foliage and would attract more wildlife and consequently the browsing of the plants. This could result in a lower survival rate, but could also positively influence the system by the input of nutrients from the dung of the animals and aeration of the soil by their trampling or digging in the soil. Transplanting may only be feasible where only a few plants are needed (Martin *et al.*, 1999). Another factor that could retard the colonisation of mine spoil by perennials is an abundance of weedy plants such as *Salsola kali* or *Atriplex lindleyi*. They have highly effective dispersal mechanisms, which make them common early migrants (MacMahon, 1987).

Given that facilitation effects are thought to outweigh competition effects in harsh environments (Callaway & Walker, 1997), I tested the following hypotheses on mine spoil:

1.) The survival of transplanted succulents would be higher when planted in clumps than alone.
2.) The growth rate (measured as stem extension) and seedset would be greater for plants in clumps than for those planted alone.

Materials and methods

Site description

The research was undertaken at a gypsum strip-mine, 5km north of Vanrhynsdorp (310 33.6" S and 180 45.2" E). It is located in the Cape Province of South Africa on the western side of the country. The vegetation of the study area is classified by Acocks (1975) as veld type 31, Succulent Karoo and by Low & Rebelo (1998) as Lowland Succulent Karoo. It is a low shrubland, dominated by members of the Mesembryanthemaceae, especially species of *Ruschia, Drosanthemum, Malephora* and *Delosperma*. Annuals and geophytes may be common after good rains but perennial grasses are scarce.

The soils of the area consist of an orthic A horizon, therefore a lack of an organic, humic, vertic or melanic topsoil and described as Red apedal or neocutanic. Then a platy type duripan or dorbank follows, which in turn is followed by a gypsic horizon (Soil Classification Working Group, 1991). After mining, the soil is rockier, with less topsoil present. The difficulty with spreading the topsoil evenly across the mined area results in the vegetation growing back patchily, with large areas of bare, hard, rocky soil.

The region is characterised by extreme summer aridity with a mean annual precipitation of 145.5mm (Desmet & Cowling, 1999), ranging from 50 to 200mm in the cool season (May to August). The average annual maximum air temperature is 23.40C and the average annual minimum temperature is 8.70C. The hottest and coldest months are February and July respectively, and average evaporation is 7.875mm/month.

Field experiments

Three local, indigenous, succulent plant species were selected for use in this experiment. The species selected were *Aridaria noctiflora* (L.) Schwantes spp. *noctiflora*, *Drosanthemum deciduum* H.E.K.Hartmann and *Psilocaulon dinteri* (Engler) Schwantes. They were chosen because they were common in the area and stored water in either their leaves, or stems or both. *Aridaria noctiflora* and *D. deciduum* both are leaf succulents, whilst *P. dinteri* is a stem succulent (Smith *et al.*, 1998). It is cheap for these plants to build succulent leaves which

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results in rapid leaf production and therefore an increase in photosynthetic area at a low cost when water is available. This ensures the deprivation of water from competitors (Midgley & Bosenberg, 1990) and gives the plant water-storage capacity for later. These factors make them well suited for transplantation. *Aridaria noctiflora* and *D. deciduum* generally occur together in a tight clump in undisturbed vegetation, whilst *Psilocaulon dinteri* is mostly found outside the clumps, but sometimes within.

Adult plants of similar size were removed from the soil, taking care not to break too many of the roots. The bulk of the soil was removed from the roots and the plants placed in open plastic bags. They were then immediately transplanted into pre-dug holes and hand-watered. The area onto which the shrubs were translocated fits the site description above. The surface is almost level with a slope varying between 0^o – 5^o. Slight micro-topography exists due to the uneven spreading of the soil and no vegetation cover existed at the time of translocation.

Ninety-six individuals of each of the species were planted alone and 96 individuals of each of the species were planted in clumps comprising one individual of each of the three species. They were planted in randomly allocated blocks of 5m x 5m in size, within 3 plots of 50m x 50m in size. Each of the three plots consisted out of a 100 blocks. The treatment was replicated once within each 5m x 5m block. The transplanting was done on the 8th of May 2000.

Transplanting success was established by measuring the new growth of two marked branches on each of the individuals. These branches were marked before the start of the growing season, halfway down the branch and at its base with enamel paint. The new growth on each of the branches was measured with vernier callipers (cm) at the end of the growing season, after flowering. The seedset (number of capsules) of each individual were recorded at the end of the flowering season. The survival after the first year was recorded in June 2001. The growth of the same marked stems of those plants that survived the transplanting and first year was also measured in the second year. It is also important to mention that no grazing took place whilst performing these experiments.

Statistical analysis

The number of plants that survived was collected as binomial data. The plants were recorded either as live or dead therefore non-parametric statistics were used to compare survival of clumped and isolated transplants between and within species. The probabilities for all variables were estimated by using the Chi -square test (STATISTICA 5.5, 1984-2000, StaSoft inc.). After testing for normality with the Kolmogorov-Smirnov and Lillefors tests the plant growth and seedset data were Box-Cox (Krebs, 1989) transformed to normalise the data. The effect of the clumping and species as treatments on the growth and reproduction of the plant was analysed by ANOVA (STATISTICA 5.5, 1984-2000, StaSoft inc.). These factors were compared within and between species. Tukey's post-hoc test was used to establish the significant differences.

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Results

Survival

The statistical analysis has shown that the species used in the translocation had differential survival. There was no significant difference between *A. noctiflora* and *D. deciduum*, however a significant difference was found between *P. dinteri* and *D. deciduum* (χ^2 = 53.36; p<0.01; df = 1) and *A. noctiflora* (χ^2 = 69.54; p<0.01; df = 1) consecutively. *Aridaria noctiflora* (41.67%) and *D. deciduum* (39.32%) survived in greater numbers than *P. dinteri* (21.09%).

The survival of clumped plants significantly differed from the survival of isolated plants (χ^2 = 9.13; p<0.05; df = 1). In total 67.36% of the translocated succulents survived. Those that were planted alone survived in greater numbers (36.63%) than those planted in clumps (30.72%). When the effect of clumping is compared within species, it can also be seen that those planted alone survived in higher numbers than those planted in clumps. No significant difference was found for *A. noctiflora* (χ^2 = 0.15; p>0.05; df = 1) although more plants survived when planted alone than in clumps.

Psilocaulon dinteri showed no significant difference in survival between clumped and non-clumped translocations (χ^2 = 3.61; p>0.05; df = 1). Again, the number of isolated survivors exceeded those planted in clumps. The survival of *D. deciduum* was significantly (χ^2 = 10.48; p=0.001; df =1) lower for clumped plants than for those planted alone. See Table 6.1 for the number and percentage survival of the various species under the different treatments.

Treatment	*A. noctiflora*	*D. deciduum*	*P. dinteri*
Clumped	79/96 = 82.2% ^{a}	64/96 = 66.6% ^{b}	34/96 = 35.4% ^{c}
Alone	81/96 = 84.3% ^{a}	87/96 = 90.6% ^{a}	47/96 = 48.9% ^{c}

Table 6.1: The number and percentage survival of the transplanted species used under the clumping and no clumping treatment. Cells with shared superscripts do not differ at the 95% probability level.

Growth

While there was a significant species effect (F = 5.861; p <0.01; error df = 566) on branch growth, there was no significant treatment or species*treatment interaction. After employing Tukey's post-hoc test it has shown that the species differences lies between *A. noctiflora* and *P. dinteri* (p <0.01) and *A. noctiflora* and *D. deciduum* (p <0.01). *Psilocaulon dinteri* had the highest average growth followed by *A. noctiflora* and *D. deciduum*. Table 6.2 shows the results of the analysis of variance, whilst Figure 6.1 shows how clumping has affected the growth of the different species.

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
Treatment	1	0.401	566	15.395	0.026	>0.05
Species	2	90.242	566	15.395	5.861	<0.01
Interaction	2	40.151	566	2.608	2.608	>0.05

Table 6.2: General Anova table for the Box-Cox transformed average growth per plant.

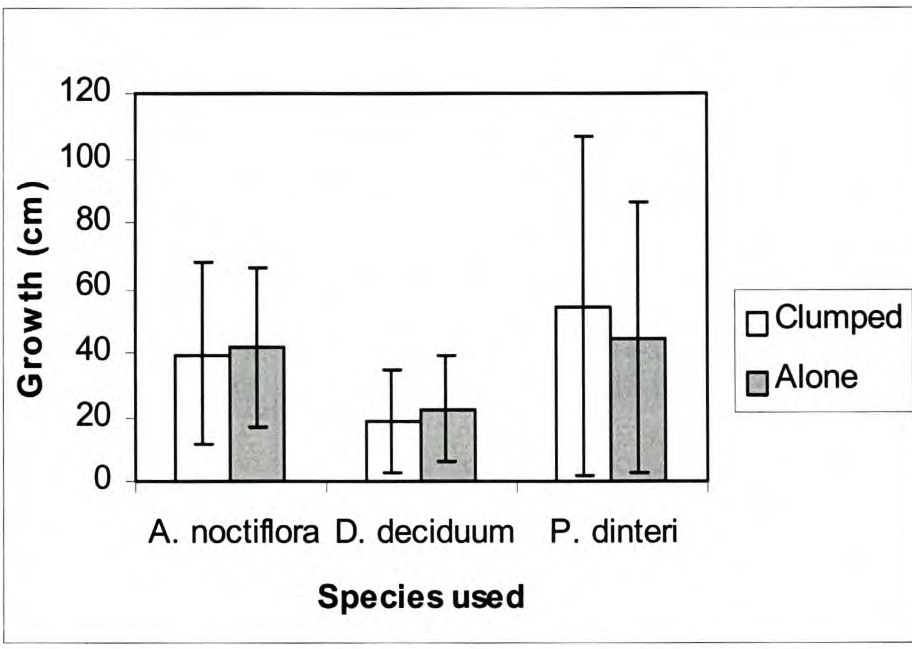

Figure 6.1: The average growth of the three species of succulent shrubs transplanted either in multispecies clumps of three plants (clumped treatment) or as single plants (alone). Error bars show the standard deviation from the mean.

Seedset

The clumping treatment had no significant effect on capsule production on any one of the species used, but did differ among species ($F = 3.49$; $p < 0.05$; error df = 367). Tukey's post-hoc test has shown that the difference ($p < 0.05$) lies between *P. dinteri* and *D. deciduum* . *Psilocaulon dinteri* formed the most capsules followed by *D. deciduum* and *A. noctiflora* consecutively.

The interaction effect of species and the clumping treatment also showed significant differences ($F=5.306$; $p<0.01$; error df=367). Tukey's post-hoc test has revealed that the difference lies between isolated *A. noctiflora* and clumped *A. noctiflora* ($p<0.01$) and also between isolated *Aridaria noctiflora* and clumped *P. dinteri* ($p<0.01$). *Aridaria noctiflora* in a clump produces much more capsules than *A. noctiflora* planted isolated. *Psilocaulon dinteri* planted in a clump produces much more seed capsules than *A. noctiflora* when planted isolated. Table 6.3 shows the results of the analysis of variance, whilst Figure 6.2 shows that clumping has no affect on the seedset (number of capsules formed) of any of the species used in this trial.

Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
Treatment	1	6.40	367	1.74	3.66	>0.05
Species	2	6.11	367	1.74	3.49	<0.05
Interaction	2	9.26	367	1.74	5.30	<0.01

Table 6.3: General Anova table for the number of seed capsules formed per plant.

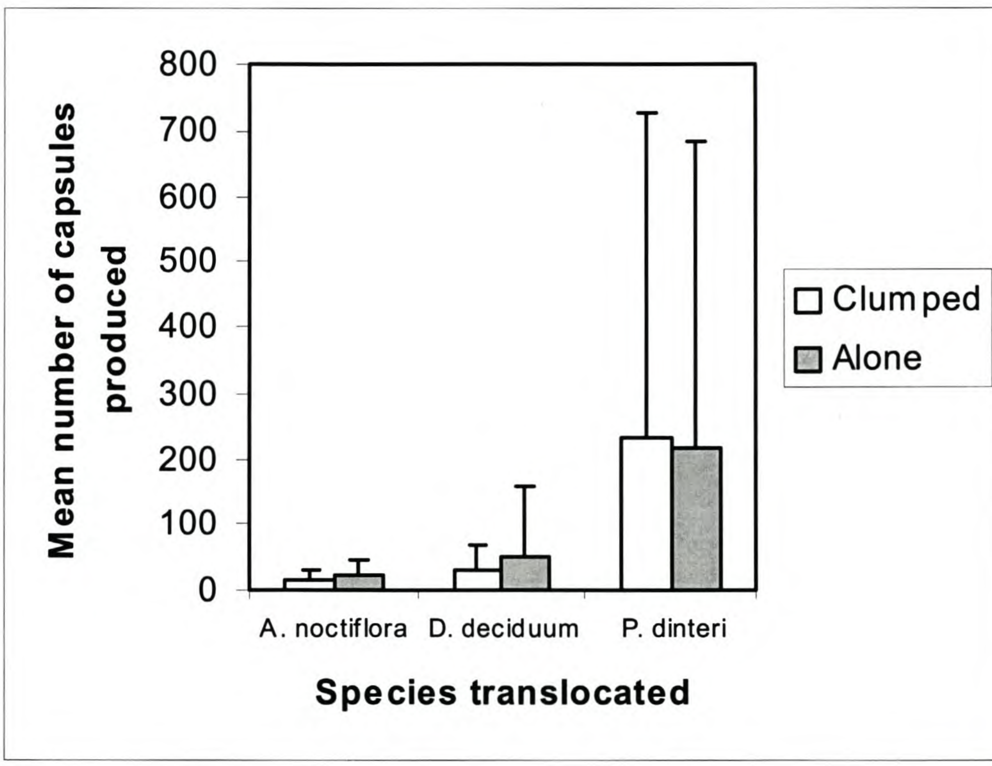

Figure 6.2: The seed capsule formation of the three species of succulent shrubs transplanted either in multispecies clumps of three plants (clumped treatment) or as single plants (alone). Error bars show the standard deviation from the mean.

Discussion

Survival

The leaf-succulent species used for transplantation in this experiment survived in greater numbers when planted alone than in clumps. This result stands in contrast with current literature that argues that the reason why plants in arid areas occur in multispecies clumps is

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due to the fact that the facilitation effect received from the clump overrides the competition within the clump (Whisenant, 1999). Eccles, (2000) argues that if the net interactions in Strandveld communities of the Succulent Karoo biome were not usually positive, then plants would not occur in clumps because there would have been strong selection against this. Eccles *et al*. (2001) showed that plants in the arid Strandveld system simultaneously experience both positive (reduced herbivory) and negative (lower water potentials) interactions between plants. They also strongly suggested that the interactions between adults would therefore be neutral. If herbivory were left out of this equation is it not possible that the net interactions might be negative? The balance of facilitation and competition appears to vary with the life stages and physiologies (Holmgren *et al*., 1997), indirect interactions with other neighbours (Miller, 1994) and the intensity of abiotic stress experienced by the interacting species (Bertness & Callaway, 1994). However, the factors that determine the balance between positive and negative are poorly understood (Callaway & Walker, 1997). A favourable microclimate within a clump is created in terms of solar radiation, wind speed, soil temperature and evaporation rates (Bochet *et al*., 1999). In the deserts of Uzbekistan a local microclimate between established belts of shrubs are created which ensures favourable conditions for the growth of other plant species (Reizvikh, 1999). Desert annual plants are often more abundant or grow larger under the canopy of shrubs.

Tielborger & Kadmon (2000) have however shown that temporal environmental variation tips the balance between facilitation and interference in desert plants. They have shown that depending on the species, the effect of shrubs on annuals changed from either negative to neutral or from neutral to positive with increasing rainfall. Therefore in very dry years shrubs would compete with annuals for survival and therefore the competition would override the facilitation effect.

Our experiments were performed in a year with below average rainfall (78mm or 53% of the long-term mean annual rainfall) and no additional watering after transplantation. The plants in clumps therefore were competing for moisture whilst those planted alone had no competition for moisture. The advantages of growing together in a clump (shading, wind protection) did not override the competition effect in this case. Some species would tolerate each other's presence since they have different strategies for exploiting environmental resources (Whisenant, 1999). Knowledge of these interactions can be used to make decisions on which species, when planted together in clumps would have the least competitive interactions.

The difference in survival of *P. dinteri* with *A. noctiflora* and *D. deciduum* may possibly be explained by the fact that *P. dinteri* is a short-lived species, whilst *A. noctiflora* and *Drosanthemum deciduum* are both long-lived species (Smith *et al*., 1998).

The negative effect that clumping had on survival of both *P. dinteri* and *D. deciduum* and not on *A. noctiflora* could be explained by the morphology of the species. Both *P. dinteri* and *D. deciduum* has shallow, lateral rootsystem whilst *A. noctiflora* has deeper, thickened roots (Smith *et al*., 1998). I therefore support the findings of Aguiar & Sala (1997) who

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showed that there was higher root competition near shrubs, which outweigh the protective effect of shrubs. In a clump there would be more competition for moisture and other resources between *P. dinteri* and *D. deciduum* and less competition with *A. noctiflora*, since the latter species will utilise the deeper soil layers for resources. I agree with Tielborger & Kadmon (2000) that facilitation would only override competition in relatively good rainfall years, but in a below average rainfall year plants will compete for moisture. Tewksbury & Lloyd (2001) made similar conclusions when they examined the effect of a long-lived desert tree on different sizes of plants in different communities in mesic and xeric habitats. They suggested that shaded microenvironments benefit established plants more in areas where water stress is less limiting. Holmgren *et al*. (1997) used a graphical model to show that the condition required for facilitation to occur is that an improvement in an environmental factor (e.g. moisture, nutrients, herbivory) under the canopy must exceed the increased demand for that factor caused by deterioration in another factor (e.g. light). The net effect of nurse canopies on the understorey may easily shift from facilitative to competitive, or vice versa, when conditions change. These principles could be applicable not only to nurse plants, but also to adult plants growing in close association.

Taking the number of surviving, translocated plants in consideration, I can agree with Burke (2001), that the replanting of disturbed areas with indigenous species is a practical solution, which could help to balance conservation, and development needs.

Growth

The higher overall growth of *P. dinteri* can be explained by the fact that it is a short-lived species and therefore would have a higher growth rate than the other two species, which are long-lived species. *Drosanthemum deciduum* outcompetes *P. dinteri* when planted in clumps, since it has a higher average growth. *Psilocaulon dinteri* therefore has significantly higher average growth when planted alone than when planted in clumps and also because it is a pioneer species which tend to invest more resources in growth. The clumping treatment doesn't influence the growth of *A. noctiflora* since it can outcompete the other two species for resources. Again this result contradicts previous research, which has shown that clumping has facilitative effects on plant growth (Eccles, 2000) and that the importance of such facilitation would increase with increasing abiotic stress. Stress results from abiotic factors such as low water, low nutrients or high temperatures, and therefore limits plant growth (Whisenant, 1999). Certain species facilitate each other's survival, whilst with others the facilitative effect of the clump is overridden by competition for water or other resources, which may vary from year to year. The responses of shrubs in clumps may therefore be the inverse in different years, which points to the importance of long-term studies to understanding species interactions in desert plant communities.

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Seedset

The clumping treatment only significantly affects *A. noctiflora* when the amount of capsules formed by the plant is investigated. Much more capsules are formed when it is clumped than when it is planted alone. One possible explanation for this pattern is that the plant invests in producing seeds when the competition for resources is high, whilst it invests in growth when there is no competition for resources. This supports the argument of Fowler, (1988) that the presence of a surviving neighbour would indicate that a spot had been favourable for seedlings. If this spot were favourable, adults in the particular location would produce more seeds in order to persist in the favourable site. The significantly higher growth of *P. dinteri* when planted alone and greater amount of seed capsules produced when clumped supports the previous statement. The opposite is true for *D. deciduum*, since this species has significantly greater growth when planted in a clump than alone, but the amount of seed capsules produced when clumped is less. The regenerative strategies are important when considering species mixes for rehabilitation purposes (Whisenant, 1999). These strategies are important because they determine the extent to which the vegetation can repair itself following damage. Callaway & Walker (1997) suggested from their experiments that the positive effects of benefactors are strong when beneficiaries are young and small. When the beneficiaries are older and larger, competitive interactions may dominate. The average numbers of seeds produced per plant at a site in the southern Succulent Karoo were 826 seeds for *Aridaria noctiflora*, 1497 seeds for *Drosanthemum hispidum*, and 3106 seeds *Psilocaulon utile* (Esler & Cowling, 1995). The results obtained in my trials were similar in that pauciennial *P. dinteri* produced the highest number of seed capsules, followed by perennials *D. deciduum* and *Aridaria noctiflora*, consecutively.

In summary, many aspects such as seedbed ecology, seed dormancy mechanisms and establishment requirements of native species is still unknown (Bellairs & Davidson, 1999; Redente & Keammerer, 1999; Sharma & Gough, 1999). In no plant community is the role of species-specific requirements for germination and establishment well understood and few communities have had the safe sites of some of their species characterised (Fowler, 1986). Very little is known about the long term success of native vegetation establishment on mined lands and the ability of rehabilitated vegetation to cope with future disturbances and therefore work needs to be conducted on the decommissioning of mine-sites in arid pastoral regions and on their resilience to grazing and the impact of grazing (Bellairs & Davidson, 1999). Uncertainty remains on how grazing pressure would impact on the transplants in these experiments. This study, although it yielded good short-term results in terms of the survival of plants, was limited by time and I therefore support current literature that there is a need for the assessment of the long-term success of native vegetation.

Callaway & Walker (1997) also address the need for long-term experiments, designed to examine the balance of competition and facilitation with varying physical stress and age, size, and density of benefactors or beneficiaries. It would contribute much to a synthesis of competition and facilitation in community ecology. In Namaqualand, South

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Africa, there is also a need for experimentation to decide which of the many factors is the most limiting to long-term ecosystem recovery. To enable us to restore lost productivity and maintain plant species diversity, information on these limiting factors on denuded and altered soils is needed (Milton & Dean, 1999). On these mined areas it seems that low soil moisture and high soil salinity would be the most limiting factors for vegetation establishment and growth (see Chapter 2).

Management suggestions

When transplanting plants for rehabilitation purposes, the most important factor to take into consideration would be the survival of the transplanted individual. The results of these trials have shown that the correct spatial arrangement and the choice of species to use are very important if you want to ensure the survival of your transplants. Strip-mining and the stockpiling of topsoil greatly reduce the amount of viable seeds in the soil (see Chapter 2) and therefore the second most important factor would be the amount of seed capsules formed. Seed limitation is often a reason why some species cannot colonise a specific site (Ash *et al.*, 1994). The seeds formed by the transplanted individuals would facilitate the dispersal of seeds onto the mined area. I would therefore consider growth of the individual plant as the least important factor.

Survival of *A. noctiflora* did not differ in response to the clumping treatment. It does however produce significantly more seed capsules when it is planted in clump. The best option would be then to plant *A. noctiflora* in clumps with a shallow-rooted species. *Psilocaulon dinteri* also produces more seeds in a clump but survives in higher numbers and grow more when isolated. In this case the survival is the most important factor and therefore *P. dinteri* should be planted alone. *Drosanthemum deciduum* survives significantly better when planted alone and grows significantly better when planted in a clump. It however produces more seed capsules when planted alone, although not significantly more. It would be more beneficial for rehabilitation purposes to plant this species alone.

Little information exists about species adaptations in this region therefore diverse species mixtures would reduce the possibility of complete failure. It is very important to employ monitoring programs and an adaptive management strategy in order to provide early detection of problems and the modification of management. In arid areas where restoration is an extremely slow process, a long-term commitment should be made in terms of monitoring.

Conclusions

Considering the results of these experiments, I reject my hypothesis and state that transplanted leaf-succulents do not necessarily survive better in clumps than alone. In this case they survived in higher numbers when planted alone. However, I have to emphasize this would not always be the case as the survival in clumps is possibly related to the

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morphology of the species used. Due to the morphological differences the different species might be in competition for resources instead of facilitating each other's establishment.

I also reject my second hypothesis and state that the growth and seedset of the transplanted leaf-succulents used were not found to be higher in clumps. The results were variable for each of the species used and clumping was not correlated with either growth or seedset. These findings would also possibly vary from year to year with different abiotic conditions.

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CHAPTER 7

GENERAL CONCLUSIONS

The main aims of this thesis were to establish guidelines for strip-mine rehabilitation and to contribute to the understanding of the vegetation dynamics of the Succulent Karoo of South Africa. There are two major factors to contend with when rehabilitating a stripmined site, namely soil quality and revegetation. For seeds to germinate and vegetation to establish the soil should contain the essential nutrients for plant growth. The availibility of suitable microsites to capture seeds and to protect seedlings against the harsh environmental conditions is also of great necessity. Plant propagules should be present in the soil or should be supplied externally to be able to revegetate the area.

In **Chapter 2** I reviewed the relevant literature on strip-mine rehabilitation with special reference to the Succulent Karoo of South Africa. I introduced a conceptual model illustrating the process of rehabilitation and the factors influencing the aims of rehabilitation (Figure 1.1, Chapter 1). I can now return to this model and the factors mentioned above with more knowledge and the ability to draw some conclusions on these aspects.

It seems that the rate at which various plant species establish and changes occur, are not related only to time since the area has been disturbed, but more to the amount of rainfall the site received after disturbance (Chapter 3). I propose that the replacement of topsoil that has not been stockpiled for more than one month and adequate rain within one year of topsoil replacement would ensure relatively fast natural colonization of the strip-mined area. Tilling, planting *A. nummularia* and sowing *A. semibaccata* do not facilitate the return of perennial, indigenous vegetation, but rather to inhibit their return. I would suggest not to seed or plant *A.semibaccata* and *A. nummularia*.

The aim of investigating the quality of the topsoil by performing bioassays and soil laboratory analysis, was to get some answers on which of the various soil parameters inhibits the establishment of vegetation (Chapter 4). I also aimed to prove that the quality of the topsoil deteriorates with time it is stockpiled. My experiments however did not allow me to draw precise conclusions on which factors are most limiting for plant recruitment, but they did convince me that the quality of the topsoil decreases with time that it is stockpiled. The nursery germination trials gave a good indication of how species diversity and richness is reduced with the stockpiling of topsoil (Chapter 4). It can however not be used to compare with the species diversity and richness established in the field, since germination of seeds is greatly influenced by the germination conditions. Field conditions were totally different from the nursery conditions where the soil was kept moist, the humidity was higher and the temperatures more moderate. The amount of seeds present in the topsoil was diluted since the highest concentration of seeds is present in the first 20mm of topsoil and not the first

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50mm. Many of the Karoo plants produce seeds with dormancy mechanisms, which also influence the germination trails, since the condition for germination would not necessarily be right or the time period of the study too short. Many of the plant species need to grow till they flower before they can be identified up to species level and the limited time period of this study did not allow all the seedlings to grow up to this stage. The germination trials were conducted in the same place so that a level of conformity was in place for all the samples.

Another question that remains is where the major seed loss occurs, in the stockpile or after the topsoil has been respread. The answer to this question could be established by running germination trials with stockpiled topsoil and topsoil that has been respread after stockpiling. The species diversity and richness can then be compared between these samples. A suggestion for future studies on the stockpiling of topsoil would be to sample the soil at different depths in a stockpile and compare the species diversity and richness of these samples with seedling emergence trials. One would expect that the topsoil deeper down in the stockpile would be of lower quality and would result in a lower species diversity and richness. The results obtained would provide information on what the maximum height of a stockpile should be, that is if stockpiling of topsoil cannot be avoided. Figure 7.1 present a summary of what happens to the seeds of the different life-history groups in the aboveground and soil seedbank after mining and stockpiling of topsoil. It also lists the factors influencing nursery germination trials and germination in the field as well as the different life-history groups from most to least abundant.

The role of microhabitat in seedling establishments and survival showed that a suitable microsite for seedlings could definitely promote the revegetation of a mined area. The study provided information contrary to popular belief that shrubs would facilitate the germination and survival of seedlings. This could be true in some cases, but it was proved in Chapter 5 that micro catchments would be more suitable. The thesis however did not provide evidence on what the reasons are why establishment of seedlings is facilitated in certain microsites. It is merely speculated that water is the most limiting factor. It was found that the balance between competition and facilitation could shift from negative to neutral or from neutral to positive depening on the rainfall of the particular year. This chapter therefore contributes to our understanding of recruitment processes.

My initial explanation for the fact that many of the perennial species occur in multi-species vegetation clumps is that they would derive some mutual protection from this situation (Chapter 6). I realised that competition for water may be one of the major forces structuring these communities and that species occurring together in clumps would have to have different root morphologies in order not to compete for the already limited resources. Another instance which allows them to occur together would be if they differ in the amount of stress that they can cope with and therefore the more tolerant species would be able to persist even if the resources is low, leaving enough resources for the less tolerant species.

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The successful translocation of local, indigenous species could ensure relatively quick results in terms of revegetation, since it is not only the plant itself that is transplanted, but also the seed that comes with it. As soon as it flowers the year after transplanting even more seed is put back into the system. The translocated plants were perennials species, which therefore ensures that perennial species which is present in low numbers on the minespoil, be returned. Little information exists about species adaptations in this region therefore diverse species mixtures would reduce the possibility of complete failure. It is very important to employ monitoring programs and an adaptive management strategy in order to provide early detection of problems and the modification of management.

Finally, I would like to conclude that research on indicators of rehabilitation success is very necessary. Very little is known about the long term success of native vegetation establishment on mined lands and the ability of rehabilitated vegetation to cope with future disturbances and therefore work needs to be conducted on the decommissioning of mine-sites in arid pastoral regions and on their resilience to grazing. In arid areas where restoration is an extremely slow process, a long-term commitment should be made in terms of monitoring, therefore research on indicators of rehabilitation success is much needed.

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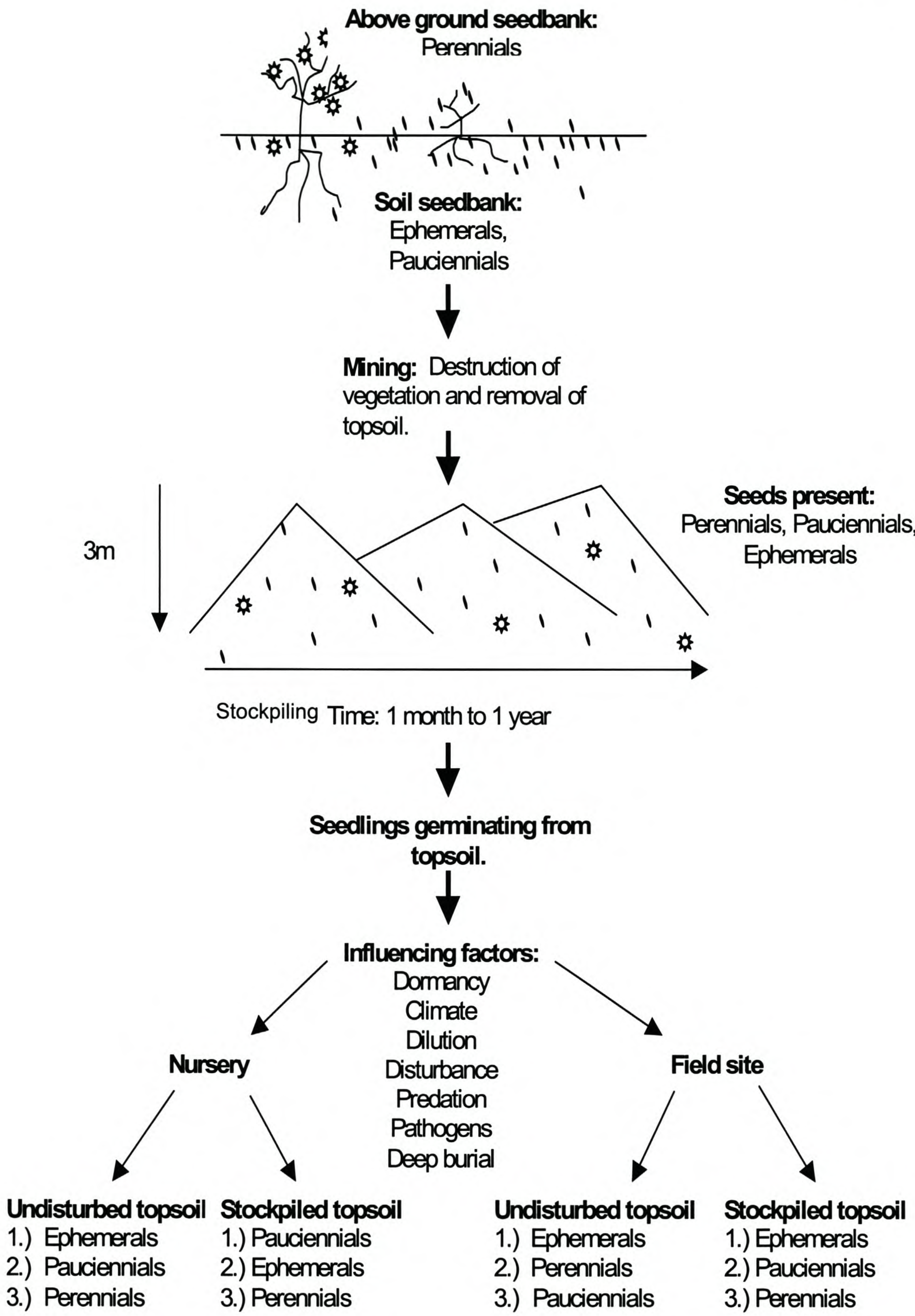

Figure 7.1: A summary of all the factors, influencing the viable soil seedbank and therefore the natural recolonization of a mined area.

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Personal communications and observation

Milton, S.J. (2001):	University of Stellenbosch, Private Bag X1, Matieland, 7613.
Fey, M.V. (2000):	University of Stellenbosch, Private Bag X1, Matieland, 7613.
Schmidt, A. (2001):	P.O. Box 12268, Die Boord, 7613.